REDUCED-RATE HERBICIDE COMBINATIONS FOR LIVING MULCH AND WEED MANAGEMENT IN A VEGETABLE CROP

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

Vinay Bhaskar

May 2017

REDUCED-RATE HERBICIDE COMBINATIONS FOR LIVING MULCH AND WEED MANAGEMENT IN A VEGETABLE CROP

Vinay Bhaskar, Ph. D.

Cornell University 2017

There is increasing interest in improving the sustainability of our farming systems. Living mulch systems can contribute to these advancements by increasing diversity and resource use efficiency, eliminating inter-row cultivations, and by reducing soil erosion by rapidly providing soil cover. However, competition with the cash crop and unreliable weed control are major challenges for the adoption of living mulches. The goal of this research was to evaluate reduced rates of herbicides as a tool for alleviating these drawbacks. It was hypothesized that the combination of living mulches and herbicides can complement each other to reduce both living mulch vigor and herbicide inputs, without compromising weed control efficacy or crop yield. Field trials were conducted during three growing seasons (2014-2016), at the Homer C. Thompson Vegetable Research Farm, in Freeville, NY, using sesbania and sunnhemp as living mulches in tomato. In 2015, there was a positive relationship between tomato yield and living mulch biomass. This relationship, however, was negative in 2016. These contrasting results were likely due to competition for water, with wet conditions occurring in 2015 and dry conditions occurring in 2016. Compared with the untreated living mulch check, the herbicide treatments reduced tomato yield losses by up to 71% in 2015 and 51% in 2016. Up to 2.5 tons ha^{-1} of dry matter was generated by the living mulches during both 2015 and 2016, with an average ground cover of 65% in 2015 and 85% in 2016. Weed biomass was reduced by as much as 97% by the living mulch-herbicide combinations. Our findings suggest that including reduced-rate herbicide applications in living mulch systems is effective in suppressing weeds without compromising living mulch biomass, soil cover, or crop yield, thereby enhancing the overall feasibility of living mulch systems.

BIOGRAPHICAL SKETCH

The author grew up in the city of Kochi in India. In 2010, he received his Bachelor of Science (B. Sc.) degree from the Kerala Agricultural University. Following his graduation, Vinay accepted appointment with the Spices Board of India as an extension agent in black pepper farming. Pursuing his interests in development of sustainable cropping systems, Vinay began his graduate studies at Cornell in 2011, in Dr. Robin Bellinder's weed science program. He conducted his Masters' research in the cotton production systems of central India. Soon after, he continued his doctoral work in Dr. Bellinder's program. Vinay received his MS in 2015. Vinay currently lives in Ithaca with his wife, Tapasya Babu.

To Robin Bellinder, an inspirational mentor because she was such an easy person to look up to.

ACKNOWLEDGEMENTS

I acknowledge my heartfelt gratitude to Dr. Robin Bellinder for this wonderful opportunity to be a part of Cornell, and learn weed science and crop production under her guidance. I am also immensely grateful to Dr. Stephen Reiners for his willingness to be my major advisor, following Dr. Bellinder's unfortunate passing in 2015. I cannot thank Dr. Reiners enough for his counsel and support. My sincerest thanks also to Dr. Antonio DiTommaso for many years of advice and encouragement, and for his help with my manuscripts. My deep appreciation to Dr. Michael Walter for his valuable insights, and for his inspirational and engrossing conversations. I am extremely thankful to Dr. Bellinder and the Horticulture Section, the Northeastern Sustainable Agriculture Research and Education, and the Towards Sustainability Fund, for providing financial support, which made my graduate study possible. I would also like to mention here some of my friends, Francis Chen, Robert Hays, Michael Schmidt, Sonam Sherpa, Herbert Tobias and Marc Warmoes, who not only made my six years at Cornell stimulating and memorable, but provided a fulfilling life outside of my work, lending to me an appreciation of the entirety of a graduate school experience. I also acknowledge the untiring support of my family, my mother, Saroja A. S., my father, S. Bhaskar Iyer and my brother, Mahesh Bhaskar. And my deepest regard for my wife, Tapasya Babu, for her enterprise and love.

TABLE OF CONTENTS

Biographical Sketch iii

Dedication iv

Acknowledgements v

Table of Contents vi

List of Tables viii

List of Figures ix

CHAPTER ONE: Herbicide Management of Living Mulches: A Review 1

Literature Cited 14

CHAPTER TWO: Living Mulch and Weed Suppression in a Reduced-Rate Herbicide System for Wide-Row Vegetables 17

Introduction 18

Materials and Methods 23

Field Preparation and Planting 23

Treatments and Data Collection 25

Data Analyses 28

Results and Discussion 29

Tomato Yield 30

Living Mulch Height, Cover and Density 37

Weed Suppression 39

Herbicide Effects on Living Mulch 43

Nutrient Composition of Plant Tissue 44

Tomato Canopy Width 49

Acknowledgements **52**

Literature Cited **53**

CHAPTER THREE: Reduced-Rate Herbicide Combinations to Target Weeds in Living Mulch Systems **72**

Introduction **73**

Materials and Methods **78**

Field Preparation and Planting 78

Treatments and Data Collection 79

Data Analyses 81

Results and Discussion **82**

Year 1 (2015) 83

Year 2 (2016) 85

Acknowledgements **93**

Literature Cited **94**

APPENDIX **110**

LIST OF TABLES

Table	Title	Page no.
2.1	Living mulch herbicide treatments during 2014, 2015 and 2016.	56
2.2	Tomato yield, and living mulch and weed parameters during the 2014 preliminary trial year.	58
2.3	Tomato yield, and living mulch and weed parameters during 2015.	59
2.4	Tomato yield, and living mulch and weed parameters during 2016.	61
2.5	Nutrient concentrations in tomato leaf tissue during 2015 and 2016.	63
3.1	Cover crop herbicide treatments during 2015 and 2016.	97
3.2	Cover crop and weed parameters during 2015.	98
3.3	Cover crop and weed parameters during 2016.	100
3.4	Cover crop and weed parameters in the herbicide-type combinations during 2015.	102
3.5	Cover crop and weed parameters in the herbicide-type combinations during 2016.	104
1 (Appendix)	Tomato yield, and living mulch and weed parameters in the inoculated living mulch test during 2016.	111
2 (Appendix)	Nutrient concentrations in tomato tissue in the inoculated test in 2016.	113
3 (Appendix)	Nutrient concentrations in sunnhemp tissue in inoculated and non-inoculated treatments in 2016.	115
4 (Appendix)	Tomato canopy width in inoculated and non-inoculated treatments in 2016.	117

LIST OF FIGURES

Figure	Title	Page no.
2.1	Relationship between tomato yield and living mulch biomass during 2015.	65
2.2	Tomato yield and weed biomass during 2015.	66
2.3	Relationships between tomato yield and living mulch biomass, tomato yield and weed cover, and weed cover and living mulch biomass during the 2014 preliminary trial year.	67
2.4	Living mulch cover, weed cover and living mulch height at different times during 2016.	68
2.5	Living mulch cover, weed cover and living mulch height at different times during 2015.	70
3.1	Cover crop cover, weed cover and cover crop height at different times during 2015.	106
3.2	Cover crop cover, weed cover and cover crop height at different times during 2016.	108

CHAPTER ONE

Herbicide Management of Living Mulches: A Review

Soil loss and degeneration have been critical issues in agriculture since the widespread intensification and mechanization of farming. Numerous strategies to control soil erosion have been evaluated. During the 1970s and 1980s, the potential to cultivate major row crops such as corn (*Zea mays* L.) in perennial sods was studied. These cropping systems were effective. Hall et al. (1984), from comparative field trials on conventional tillage and no-till plus living mulch, reported that soil sediment loss in the conventional system was 32 tons ha^{-1}, compared with only 0.04 to 1.1 tons ha^{-1} in no-till plus living mulch. In the same experiment, water loss through surface run-off from the conventional plots was 10 cm, while it was only 1 cm or less in no-till plus living mulch. The researchers also studied the differences in pesticide losses (through run-off and soil erosion) between the cropping systems. Loss of cyanazine herbicide used in the experiment was 257 g ha^{-1} in the conventionally tilled system, compared to 8.8 g ha^{-1} in no-till plus living mulch. In no-till plus corn residue, cyanazine loss was 32 g ha^{-1}.

Compared with mulches that are terminated before crop planting, living mulches are also more effective in reducing nitrate losses (Thomas et al. 1973). In case of a non-living mulch, the macro-pores created by decaying roots permit deeper and quicker movement of water, and along with it, nitrates. Compared with residue, living mulches may also mitigate the adverse effects of water stagnation in poorly drained soils. Evaporative losses of soil moisture from soil covered with non-living mulch is extremely low; approximately six times lower than from bare soil according to an estimate by Thomas et al. (1973). Leaching of nitrates dissolved in soil water can be decreased by the increased evapo-transpiration losses from living mulch systems.

Intention of living mulch research has primarily been to obtain maximum crop yield and soil conservation. So, living mulches were typically suppressed before crop planting, and then allowed to recover and grow from fall through spring, thereby enabling considerable soil cover and biomass production during the fallow seasons (Hartwig and Hoffman 1975). Since perennial sod systems entail reduction in tillage, they additionally contribute to soil erosion control. When planting crops into a perennial sod, it is possible to replace primary tillage operations with herbicides for sod suppression (Moomaw and Martin 1976). This can be highly beneficial in erodible soils, when crops are conducive to no-till. Annual living mulches can also reduce tillage because their presence is an excellent deterrent to inter-row tillage during the growing season.

Even though living mulches can provide all these agro-ecosystem benefits, living mulch-cash crop competition is a major challenge in the adoption of living mulch systems. And when herbicides used to suppress living mulches are ineffective, there can be significant losses in crop yield (Hartwig 1976). From a living mulch experiment in corn, Hall et al. (1984) reported that even high rates of cyanazine could be incapable of adequately suppressing living mulches, thus leading to reductions in corn yield from excessive living mulch competition. Echtenkamp and Moomaw (1989) also reported that when hairy vetch (*Vicia villosa* Roth) was not suppressed by the herbicide (atrazine) used, corn yields were severely reduced. In another experiment in corn, where the biomass of the chemically suppressed crownvetch [*Securigera varia* (L.) Lassen] mulch was the highest, corresponding corn yield was 77% lower (Linscott and Hagin 1975). In the same study, crownvetch biomass and cover were reduced by 68 and 66%, respectively, when corn yield was maximum. In vegetables, Hughes and Sweet (1979) reported unacceptable yield losses in cabbage (*Brassica oleracea* var. *capitata* L.) and beets (*Beta vulgaris* L.) when herbicide applications did not suppress living mulches (oats (*Avena sativa* L.), rye and perennial ryegrass (*Lolium perenne* L.)). Besides herbicides, cultural management techniques for living mulches have also been explored. When living mulches are cut back, their recovery can be undesirably quick, resulting in crop yield losses. Living mulch regrowth from herbicide control has been reported to be only half that from non-chemical management (Hartwig 1976).

Therefore, beyond their use in weed control, herbicides may additionally be required to achieve sufficient living mulch control. In case of corn planted into alfalfa (*Medicago sativa* L.) sod, separate herbicide applications had to be used for control of alfalfa and weeds in order to prevent declines in corn yield (Moomaw and Martin 1976). In this way, many studies have reported the need for increase in chemical inputs in living mulch systems. And, reduction in synthetic chemical inputs was not an important consideration in much of the living mulch research, which were mostly in the 1970s and 1980s. Besides herbicides, supplemental fertilizer applications, especially of nitrogen, were also used to maintain crop yields (Robertson et al. 1976; Moomaw and Martin 1976). However, supplemental nitrogen applications may not only be contradictory to the sustainability aspects of living mulch systems, it is also relatively ineffective. Studies in vegetables have shown that, while addition of nitrogen to compensate for the living mulch increases crop yield, it does not provide yields comparable to conventional sole vegetable stands (Brainard et al. 2004). This additional nitrogen might also increase weed pressure. Brainard et al. (2004) reported that supplemental nitrogen favored weeds, sometimes increasing weed biomass by more than five times.

As with provision of extra nitrogen, increased herbicide input also has its drawbacks. Beyond the environmental impacts of increased herbicide use, living mulches were damaged too severely in order to obtain maximum crop yields (Elkins et al. 1979; Hartwig and Hoffman 1975). And this was a major constraint in gaining the full benefits of a living mulch system. Elkins et al. (1979) reported that, in a corn crop grown in grass sod, while acceptable crop yield was obtained, sod biomass was typically cut in half by the herbicide applications.

Weed control provided by combinations of living mulches and herbicides have been reported to be better than from herbicides alone; and when herbicides damage living mulches too severely, weed suppression can be impaired (Hartwig 1977). Hughes and Sweet (1979) reported adequate suppression of broadleaf weeds when a perennial ryegrass living mulch that was chemically suppressed remained upright and maintained dense cover. On the other hand, there was an increase in broadleaf weed population when the rye was excessively injured by the herbicides. Wheat (*Triticum aestivum* L.), which was also tested as a living mulch in the Hughes and Sweet (1979) study, was adequately suppressed by the herbicide applications, but provided little weed control because of poor soil cover. Such increase in weed growth following excessive herbicide injury to the living mulch were observed in other experiments also (Echtenkamp and Moomaw 1989).

But, there may not be a need to suppress living mulches severely. Beyond their contributions to weed control, living mulch growth has also demonstrated the ability to be dissociated from crop growth, with no impacts on crop yield (Cardina and Hartwig 1980). Living mulches have been reported to even improve crop yields. For example, in sweet corn, compared with sweet corn grown without living mulches, yield was 75% higher when legume living mulches were planted in strips between sweet corn rows (Vrabel et al. 1981). In the Vrabel et al. (1981) study, nitrogen concentration in the sweet corn grown along with living mulches was also 50% higher than in the mono-cropped sweet corn. When soil and weather conditions are suitable, crop yields comparable to conventional systems can be attained in living mulch systems using appropriate herbicide types, application rates and application timing.

For example, Echtenkamp and Moomaw (1989) reported that, in an above-average rainfall year, there were no reductions in corn yield due to living mulch competition. Adams et al. (1970) also reported that, in the absence of irrigation, yield was reduced in corn grown with grass living mulch, due to competition for water. In vegetables, Brainard and Bellinder (2004) reported that broccoli (*Brassica oleracea* L. var. *botrytis* L.) yields were adversely affected by an intercrop of winter rye (*Secale cereale* L.) when irrigation was inadequate during dry conditions. Chase and Mbuya (2008) investigated the potential for cultural management of living mulches in organic broccoli production. Here, the combined biomass of living mulches and weeds affected crop yield more than the weed biomass alone. In this study, perhaps the distance between the broccoli crop and the living mulch was not large enough to permit distinction between the effects of the living mulch and weeds.

Since living mulches can avert losses in crop yields, herbicide applications must control living mulch growth without damaging them severely. Living mulch recovery is crucial for soil cover, biomass production, weed control, and other sustainability benefits that are expected from living mulch systems. But, although chemical suppression of living mulches has been explored as a promising strategy, lower herbicides rates were reported to be ineffective, while higher rates injured the living mulches too severely (Hughes and Sweet 1979). In herbicide management of living mulches, lower herbicide rates might be a better option. Reduction in application rates can translate to an overall reduction in herbicide input, thereby serving the sustainability goals of living mulch systems. In addition, lower herbicide rates promote better living mulch recovery, which in turn can enhance weed suppression. Contribution of living mulches towards weed control provides excellent opportunity for improving the feasibility of reduced herbicide rates.

Lower herbicide rates might be sufficient for suppression of living mulches if they are planted at approximately the same time as the cash crop. When crops are planted into larger living mulches, additional herbicides might be required to suppress living mulches (Peters and Currey 1970). Regarding annual and perennial living mulch systems, much greater amounts of herbicides may be required for suppression of perennial mulches. From a perennial crownvetch sod study in corn, Cardina and Hartwig (1980) reported that the living mulch gained vigor each season, becoming decreasingly susceptible to herbicide treatments. During the third year of the experiment, highest corn yield was obtained from the herbicide treatment that provided the greatest degree of crownvetch suppression.

Vrabel et al. (1980) explored some fundamental aspects of living mulch systems. Living mulches were planted at three different times: five weeks prior to sweet corn planting, at the time of sweet corn planting, and five weeks after. Two methods of living mulch seeding were also tested: broadcasting, and drilling into 45 cm strips between the sweet corn rows. The researchers reported that both the earliest planting of living mulch and the broadcast method of living mulch seeding reduced sweet corn yield. And, in case of the latest planting, weed suppression was unacceptable. Planting the crop and the living mulch at the same time was concluded to yield the most satisfactory outcomes.

Earlier planting of living mulches relative to the crop can increase living mulch-crop competition (Brainard and Bellinder 2004). But, since reduction in soil disturbance is an important aspect of soil conservation, delayed planting of living mulches may be of concern if inter-row tillage becomes essential for weed control. In an earlier study in cabbage intercropped with legume living mulches, even though presence of the living mulch reduced the number of inter-row cultivations required to reach the reference weed biomass (weed biomass from hand-weeded control), cultivations were necessary to prevent cabbage yield losses (Brainard et al. 2004). Moreover, delayed living mulch planting will leave the soil surface exposed for a considerable amount of time. This is particularly serious if soil cover is not adequate during the period of maximum rainfall, when soil displacement and erosion are likely to be the greatest.

When living mulches are planted early, their capacity for weed suppression increases. Brainard and Bellinder (2004) reported that weed suppression by a rye living mulch in broccoli was better when the rye was planted on the same day the broccoli was transplanted. But, this did result in the rye being too competitive with the broccoli crop. On the other hand, when rye was planted 10 or 20 days after broccoli transplant, crop yield was unaffected, but weed suppression was poor. Early planting of the rye also increased the resource use efficiency of the intercropping system by generating greater amounts of biomass. In the Brainard et al. (2004) study in cabbage intercropped with legume living mulches, living mulch competition with weeds and living mulch biomass production were highest when living mulches were seeded earlier, and cabbage yield was highest when living mulch sowing was delayed.

Living mulch planting time is one factor that can be manipulated to reduce herbicide rates. Herbicide rates may also be reduced by choosing appropriate living mulch species. Cool season grass species have been considered for this purpose (Elkins et al. 1979; Peters and Currey 1970). The expectation is that cool season grass living mulches would automatically go dormant during summer. In a corn planted into grass sod, corn yields were reduced more by a warm season Coastal bermuda grass [*Cyanadon dactylon* (L.) Pers.], than by a cool season tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] (Adams et al. 1970). While this strategy can reduce herbicide input, soil cover, biomass production and resource use efficiency by the living mulch will be lower. Furthermore, dormant living mulches might be less competitive with weeds than vigorously growing ones.

Cover crops or living mulches can be more effective in weed suppression when they are mixtures of grasses and legumes, instead of a single species (Liebman and Dyck 1993). However, when living mulch management is through herbicides, the differences between the species/plant types in their sensitivity to the herbicide applications can be problematic. This problem can be exacerbated by the suppression of less competitive species by the more vigorous species. Earlier studies have reported excessive herbicide injury to legumes like birdsfoot trefoil (*Lotus corniculatus* L.) and crownvetch when they were grown in mixtures with grasses such as smoothbrome (*Bromus inermis* Leyss.) (Hartwig and Hoffman 1975).

Overall herbicide input can be reduced if efficacy of herbicide applications can be increased without increase in the amount of herbicide used. In case of herbicides with poor post-emergent activity, surfactants can be included to increase weed injury and to target more weeds (Currey and Cole 1966; Liu et al. 1966). So, herbicides with primarily pre-emergent activity could be used along with surfactants in order to increase living mulch and weed injury, while at the same time providing some residual activity against future weed emergence. This can facilitate reduction in herbicide rates (Dickerson and Sweet 1968; Wilson and Waterfield 1968). In sweet corn, atrazine at rates five to ten times lower than commercially recommended rates, when applied with a surfactant, was able to provide weed control comparable to the recommended rate (Akobundu et al. 1975).

Therefore, by boosting the relatively poor post-emergent activity of primarily pre-emergent herbicides, their residual activity could be used to the advantage of the living mulch, while simultaneously improving their effects on already emerged weeds. Hoffman and Hartwig (1975) also emphasized the benefits of using short residual herbicides in management of living mulch systems, especially in the maintenance of adequate soil cover. Use of such herbicides may also be beneficial in weed control. If herbicides with residual activity are not used, the number of herbicide applications required for adequate weed control may increase. In a living mulch study in corn, an atrazine plus propachlor combination, separate from the herbicide treatments themselves, had to be used in order to prevent losses in corn stand due to weeds (Moomaw and Martin 1976).

Primarily pre-emergent herbicides that have poor post-emergent activity, when used with surfactants can be useful in living mulch systems. When applied early in the season, not long after living mulch emergence, the surfactants can boost living mulch injury. But, the pre-emergent nature of the herbicide may ensure that the living mulches are not damaged too severely. In addition, by providing residual soil activity against weed emergence, these herbicide applications can create a less competitive environment for the living mulch. If the living mulch emerges sooner than weeds, then the herbicide application will injure weeds more because of their smaller size. This opportunity for good establishment may enable the living mulch to withstand a subsequent application of a herbicide with greater post-emergent activity. Potentially, this herbicide application will also affect weeds more due to their smaller size, compared with the living mulch.

Earlier experiments on living mulches have used combinations of herbicides for living mulch control (Cardina and Hartwig 1980; Linscott and Hagin 1975; Hartwig 1976; Hartwig 1977). A combination of different types of herbicides may be able to control a larger variety of weeds, especially when lower application rates are used. These herbicide combinations were applied as pre or post emergent, or pre-plant incorporated applications. However, they were typically applied in a single application. Further research is required to examine the benefits of applying two or more herbicides, not in combination, but in separate applications. The differences in effects of different herbicides on living mulch and weeds could provide living mulches with a competitive advantage over weeds. By lowering the quantity of herbicides in each application, recovery of living mulch from herbicide injury can be minimized, and drastic decreases in soil cover for extended periods of time can also be avoided.

When herbicide applications are temporally spaced out, they might be able to suppress living mulches (and weeds) for longer periods. In no-till corn, when a combination of contact and residual herbicides were sprayed in a single application for the control of a bahiagrass (*Paspalum notatum* Flueggè) living mulch sod, recovery of bahiagrass was quick enough to compete with the corn crop for water and nutrients (Robertson et al. 1976). From another study in corn, where multiple living mulch species were tested, Hoffman and Hartwig (1975) concluded that evaluation of herbicide timings and rates was important in providing consistent soil protection. When multiple herbicide applications are carried out, careful consideration of post-harvest intervals for the crop is required.

Seed set by living mulches is an important consideration in annual living mulch systems, due volunteer weed issues during the subsequent year. Earlier living mulch studies in the northeastern United States have only looked at typical cover crop species used in the region. This is in part because the experiments were largely focused on perennial living mulch systems where living mulches must withstand the winter, and begin regrowth in early spring. However, in annual living mulch systems like vegetables, where no-till is not prevalent, termination of living mulches might not only be an additional operation, but also a tedious one since this would potentially happen around harvest time. In this regard, tropical or sub-tropical living mulch species may be advantageous because they would have poor tolerance to the temperatures towards the end of summer. Selection of species with longer lifespans could also preempt early flowering.

Due to the established soil and environmental benefits, and noted agronomic and economic potential of living mulches, it would be valuable to develop methods to attain consistent results in herbicide managed living mulch systems. Further research is also required to make these cropping systems more effective, feasible, and perhaps even beneficial to the cash crop. However, little emphasis has been placed on herbicide reduction in living mulch systems. Considering current interest in improving agricultural sustainability and reducing chemical inputs, strategies must be developed to attain the desired outcomes from living mulch systems using lower herbicide rates, fewer herbicides and fewer herbicide applications. More information is also required on annual living mulch systems for vegetables, and on the potential of novel living mulch species.

Future research must strive to focus on these aspects of living mulch systems. While maximization of the quantity of consumables obtained from farming is not inconsequential, small losses in crop yield may have to be endured on the path to agricultural sustainability. Subsequently, with advancement in living mulch technology and soil improvement, satisfactory economic profits from either lower inputs or greater crop yields, may be conceivable. In living mulch research, beyond the scope of solely crop yield, attention must be paid to understanding in depth, the ecological interactions between crop, living mulch and weeds, especially as it pertains to the disturbance caused by herbicide applications.

Literature cited

Adams WE, Pallas JE, Dawson RN (1970) Tillage methods for corn-sod systems in the Southern Piedmont. Agron J 62:646–649

Akobundu IO, Sweet RD, Duke WB, Minotti PL (1975) Weed response to atrazine and alachlor combinations at low rates. Weed Sci 23:67–70

Brainard DC, Bellinder RR (2004) Weed suppression in a broccoli–winter rye intercropping system. Weed Sci 52:281–290

Brainard DC, Bellinder RR, Miller AJ (2004) Cultivation and interseeding for weed control in transplanted cabbage. Weed Technol 18:704–710

Cardina J, Hartwig NL (1980) Suppression of crownvetch for no-tillage corn. Pages 53–58 *in* Proceedings of the 34th Northeastern Weed Science Society Meeting

Chase CA, Mbuya OS (2008) Greater interference from living mulches than weeds in organic broccoli production. Weed Technol 22:280–285

Currey WL, Cole RH (1966) Comparisons of atrazine, atrazine-surfactant and atrazine-oil mixtures. Pages 297–300 *in* Proceedings of the 20th Northeastern Weed Science Society Meeting

Dickerson CTJ, Sweet RD (1968) Atrazine, oil, and 2,4-D for postemergence weed control. Pages 64–75 *in* Proceedings of the 22nd Northeastern Weed Science Society Meeting

Echtenkamp GW, Moomaw RS (1989) No-till corn production in a living mulch system. Weed Technol 3:261–266

Elkins DM, Vandeventer JW, Kapusta G, Anderson MR (1979) No-tillage maize production in chemically suppressed grass sod. Agron J 71:101–105

Hall K, Hartwig NL, Hoffman LD (1984) Cyanazine losses in runoff from no-tillage corn in “living” and dead mulches vs. unmulched, conventional tillage. J Environ Qual 13:105–110

Hartwig NL (1976) Legume suppression for double cropped no-tillage corn in crownvetch and birdsfoot trefoil removed for haylage. Pages 82–85 *in* Proceedings of the 30th Northeastern Weed Science Society Meeting

Hartwig NL (1977) Nutsedge control in no-tillage corn with and without a crownvetch cover crop. Pages 20–23 *in* Proceedings of the 31st Northeastern Weed Science Society Meeting

Hartwig NL, Hoffman LD (1975) Suppression of perennial legume and grass cover crops for no-tillage corn. Pages 82–88 *in* Proceedings of the 29th Northeastern Weed Science Society Meeting

Hoffman LD, Hartwig NL (1975) Perennial soil conserving cover crops for no-till corn. Page 89 *in* Proceedings of the 29th Northeastern Weed Science Society Meeting

Hughes BJ, Sweet RD (1979) Living mulch: A preliminary report on grassy cover crops interplanted with vegetables. Page 109 *in* Proceedings of the 33rd Northeastern Weed Science Society Meeting

Liebman M, Dyck E (1993) Crop rotation and intercropping strategies for weed management. Ecol Appl 3:92–122

Linscott DL, Hagin RD (1975) Potential for no-tillage corn in crownvetch sods. Page 81 *in* Proceedings of the 29th Northeastern Weed Science Society Meeting

Liu LC, Ilnicki RD, Regan JB, Visinski EJ (1966) Naphthenic and paraffinic oils as adjuvants in atrazine and linuron sprays for weed control in corn. Pages 309–316 *in* Proceedings of the 20th Northeastern Weed Science Society Meeting

Moomaw RS, Martin AR (1976) Herbicides for no-tillage corn in alfalfa sod. Weed Sci 24:449–453

Peters RA, Currey WL (1970) Influence of sod species in no-tillage corn production. Pages 421–425 *in* Proceedings of the 24th Northeastern Weed Science Society Meeting

Robertson WK, Lundy HW, Prine GM, Currey WL (1976) Planting corn in sod and small grain residues with minimum tillage. Agron J 68:271–274

Thomas GW, Blevins RL, Phillips RE, McMahon RL (1973) Effect of a killed sod mulch on nitrate movement and corn yield. Agron J 65:736–739

Vrabel TE, Minotti PL, Sweet RD (1980) Seeded legumes as living mulches in sweet corn. Pages 171–175 *in* Proceedings of the 34th Northeastern Weed Science Society Meeting

Vrabel TE, Minotti PL, Sweet RD (1981) Legume sods as living mulches in sweet corn. Pages 158–159 *in* Proceedings of the 35th Northeastern Weed Science Society Meeting

Wilson HP, Waterfield RL (1968) Activity of herbicides in sweet corn. Pages 47–53 *in* Proceedings of the 22nd Northeastern Weed Science Society Meeting

CHAPTER TWO

Living Mulch and Weed Suppression in a Reduced-Rate Herbicide System for Wide-Row Vegetables

Introduction

There is considerable interest to improve the sustainability of farming systems, especially in the realm of soil conservation and improvement. Soil erosion was recognized as a grave issue numerous decades ago. During this time, efforts have been made to minimize the frequent and disruptive tillage that was prevalent, and to maintain soil cover during fallow seasons. One strategy that was evaluated for this purpose involved the growing of row crops in living mulches. The focus of these experiments was on maintaining perennial sods in no-till corn (*Zea mays* L.) production. Since the presence of living mulches would make inter-row cultivation during the season difficult, living mulch systems go hand-in-hand with reduced tillage. In the case of crops planted into existing sod, it is also possible to eliminate initial tillage for field preparation by using herbicides to suppress the sod (Moomaw and Martin 1976).

This combination of reduced tillage and living mulch is effective in minimizing soil erosion and, water and pesticide run-off from fields. Hall et al. (1984) reported that, compared with soil erosion losses of up to 32 tons ha^{-1} in conventional tillage, in a no-till system consisting of a living mulch, soil losses amounted to only 0.04 to 1.1 tons ha^{-1}. Cyanazine herbicide run-off was also reduced to 8.8 g ha^{-1} compared with 257 g ha^{-1} from conventional management. Furthermore, water infiltration increased by 97 to 99% in the no-till plus living mulch system. Compared with non-living mulches, living mulches are also more effective in reducing nitrate losses with the downward leaching of soil water (Thomas et al. 1973).

Even though living mulches have these sustainability benefits, living mulch-cash crop competition and unreliable weed control are major challenges in living mulch systems. Research on living mulches has explored the feasibility of these cropping systems. Most of this research focus has been on perennial systems in no-till corn for soil conservation, and use of additional fertilizers and herbicides to maintain crop yield. However, there are few studies that have assessed chemically managed living mulch systems. Specifically, little work has been done on: 1) reduced tillage systems, or where no-tillage is difficult (like vegetable cropping systems); 2) annual living mulches (as opposed to perennial sod systems); 3) reduction in herbicide inputs; 4) novel living mulch species and 5) information on the influence of herbicide type and timing on the performance of the living mulch and weeds, and crop yield.

Several living mulch studies in both corn and vegetables have reported that maximum crop yields were realized only when herbicide applications severely damaged the living mulch stand (Hartwig and Hoffman 1975; Hughes and Sweet 1979; Linscott and Hagin 1975). In these cases, herbicides were used to suppress the living mulch in addition to their use for weed control (Moomaw and Martin 1976; Vrabel et al. 1981). Non-chemical methods such as mowing were also evaluated as a tool for living mulch management, but living mulches recovered too quickly and became excessively competitive with the crop (Hartwig 1976).

Living mulch growth can be controlled such that they do not adversely affect the cash crop. For example, in a crownvetch [*Securigera varia* (L.) Lassen] living mulch experiment in corn, Cardina and Hartwig (1980) reported that living mulch growth did not negatively affect crop yields. Brainard and Bellinder (2004) also observed the capacity of living mulches in a vegetable system, to compete solely with weeds. Some previous studies have even reported increased crop yields in living mulch systems. Sweet corn planted into a white clover (*Trifolium repens* L.) living mulch had 75% higher yield and 50 % higher leaf nitrogen content compared with corn not planted into a living mulch (Vrabel et al. 1981). Elkins et al. (1979) reported acceptable corn yields even when at least 50% of the grass sod was maintained through herbicide applications.

Reductions in chemical inputs were not a priority in earlier perennial living mulch system studies. To prevent crop yield losses, supplemental nitrogen was also provided in the perennial sods (Robertson et al. 1976). Increased synthetic nitrogen input to compensate for the living mulch might not be a sustainable cropping system approach. Moreover, additional nitrogen inputs have been reported to favor weeds over crops. Brainard et al. (2004) reported a five-fold increase in weed biomass in cabbage (*Brassica oleracea* var. *capitata* L.) with the addition of supplemental nitrogen.

There is potential for reduction in herbicide inputs in living mulch systems because the contribution of living mulches to weed suppression is substantial. When injury to living mulches from herbicide applications is not too severe, weed growth is considerably reduced (Hartwig 1977; Hughes and Sweet 1979). On the other hand, severe living mulch injury can lead to high weed pressure. Adequate cover crop recovery from herbicide applications, and consequently longer lasting stands, are possible when herbicide rates are reduced (Elkins et al. 1982). Adequate weed suppression can also be achieved using herbicides at low rates of application (Akobundu et al. 1975; Hamill and Zhang 1995). Rates of soil residual herbicides can be decreased, and post-emergent activity of primarily pre-emergent herbicides can be increased, by addition of surfactants

(Akobundu et al. 1975; Currey and Cole 1966; Dickerson and Sweet 1968; Liu et al. 1966; Wilson and Waterfield 1968). In this way, the benefits of these two different types of herbicides can be obtained. However, the potential for herbicide reductions has not lead to the testing or establishment of acceptable application rates in vegetables or corn (Hughes and Sweet 1979; Echtenkamp and Moomaw 1989).

In a living mulch trial in sweet corn, Vrabel et al. (1980) reported that yields were severely reduced when planted into existing mulches. Moreover, drilling living mulch seeds into the crop inter-rows did not cause yield losses, whereas broadcast seeding did reduce yields. Planting the living mulch and the crop at the same time was the most effective in achieving maximum benefit from the living mulch system. Brainard et al. (2004) and Brainard and Bellinder (2004) reported that weed suppression and living mulch biomass production increased when intercrops were planted earlier in the season in cabbage and broccoli (*Brassica oleracea* L. var. *botrytis* L.). Crop yields however, were adversely affected by early-planted intercrops in these studies. For late-planted intercrops, multiple inter-row cultivations (before living mulch seeding) were required to achieve acceptable crop yields. Late planted living mulches may also result in reduced and inadequate soil cover, especially during the wettest periods, which is undesirable in for soil conservation. When crops are planted into large or perennial living mulches, greater quantities of herbicides and fertilizers maybe required (Peters and Currey 1970; Cardina and Hartwig 1980). For vegetables, planting into existing mulches may also be difficult (Shelby et al. 1988).

When living mulches are used in cropping systems (e.g. vegetables) that include some form of annual tillage, it would be advantageous to select living mulch species that will not set seeds. Furthermore, since living mulch termination operations would be difficult (especially as such operations occur around harvest time), the use of tropical/sub-tropical living mulch species that do not set seeds may prove advantageous rather than more typical cover crop species used in the northeastern United States. Sesbania and sunnhemp were expected to be susceptible to the lower temperatures of central New York State even as early as mid-September. Use of such novel species could also reduce the possibility of the living mulch serving as an alternate host for a regional pest or disease.

Assessment of living mulches in terms of crop yield and soil conservation is important. However, in this experiment, emphasis was also placed on exploring the influence of herbicide applications on the competitive interactions between the living mulch, weeds and the crop. The main objectives of the trial were to study the effects of: 1) the living mulch-herbicide combinations on tomato growth and yield; 2) the herbicide treatments on living mulches and weeds; and 3) the living mulch-herbicide combinations on weed suppression.

Materials and Methods

Field trials were conducted at the Homer C. Thompson Vegetable Research Farm in Freeville, NY, during 2014, 2015, and 2016, on Howard gravel loam soils (Loamy-skeletal mixed mesic Glosoboric Hapludalf) with pH = 6.0 to 6.6. The trials were located in different fields each year. Sesbania [*Sesbania sesban* (L.) Merr.] and sunnhemp (*Crotalaria juncea* L.), both tropical/sub-tropical legumes were used as living mulches. Tomato was chosen as the vegetable crop for two main reasons. One, it can be planted in relatively wide rows, enabling easier accommodation of the living mulch. And two, it has a relatively greater number of herbicides registered for use in it, providing more choices for herbicide treatments.

Field preparation and planting: Field preparation consisted of moldboard plowing, followed by disking and harrowing. N, P and K, were all applied at the rate of 100 kg ha^{-1} using 13-13-13 (NPK) fertilizer. Additional fertilizers were not applied to compensate for the presence of the living mulch. During the last week of May, sesbania and sunnhemp were seeded at a row spacing of 23 cm using a grain drill. Sesbania was planted at a rate of 40 kg ha^{-1}. The grain drill lacked a suitable setting for sunnhemp seeds; and as such, sunnhemp was seeded at rates of approximately 55, 50 and 90 kg ha^{-1}, in 2014, 2015, and 2016, respectively. In 2015, a push behind seeder was employed after this initial seeding to increase seeding rate. Due to the absence of a smaller drill seeder capable of planting within tomato rows, the entire field was first planted to the living mulches. Then, immediately after the emergence of the living mulch, rows were hand-hoed to accommodate the tomato crop. Since tomato was planted at 122 cm row spacing, living mulch rows were removed and left in sets of three. This resulted in three rows of living mulch, spaced at 23 cm, and 46 cm from the tomato row on either side.

'Mountain Fresh' fresh market tomato variety was seeded in the greenhouse in 72-plug seed starter trays during the last week of April. Four-to-five week old transplants were hand-transplanted into the field during the first or second week of June, at a plant-to-plant spacing of 46 cm. Tomato was subjected to a hardening process outdoors in cold frames for a few days before transplanting. In 2016, to facilitate easier and deeper planting of tomato transplants in the stony soil, a tractor driven two-tine attachment was used to make furrows, approximately 20 to 25 cm deep, along where the tomato would be transplanted. Care was taken to prevent tractor wheels from injuring the living mulch.

Experimental plots were set up in a randomized complete block design with four replicates. The two living mulch species were planted into 3.7 m wide strips. Each one of these strips served as a replicate, and the individual treatments were randomly assigned to plots within these living mulch strips. Due to poor emergence and establishment of sesbania during both these years, sesbania was not used in 2016. Individual plots measured 3.7 by 7.6 m in 2014, and 3.7 by 4.6 m in 2015 and 2016. Each plot consisted of four tomato rows, of which the two central rows were harvested to estimate tomato yield. Irrigation was provided as required using over-head sprinklers. Due to above-average rainfall in 2015, irrigation was not needed that year. In contrast, irrigation was required numerous times in 2016.

Treatments and data collection: In 2014, the trial consisted of five herbicide treatments, a mowing treatment, and a hand-weeded, weed-free control (Table 2.1). The herbicide treatments were one rate of halosulfuron, two rates of metribuzin and two rates of rimsulfuron. All herbicide applications were made post-emergent with respect to both the tomato and the living mulches, and they were all used with a non-ionic surfactant at a rate of 0.25% of the spray volume. Each herbicide treatment consisted of two applications of one herbicide at a fixed rate (Table 2.1). The only other herbicides used in the experiments were the grass herbicides sethoxydim and clethodim (never in combination), which were blanket applied over the field at recommended rates for tomato. These applications were made around the same time as the first set of herbicide treatment applications. It was expected that suppression of grass weeds by the reduced rates of the primarily broadleaf treatment herbicides would not be adequate. The broadleaf living mulches did not show any injury from the application of the grass herbicides.

Herbicides and application rates were evaluated for efficacy in the greenhouse, and in the field, in strips of sesbania and sunnhemp established on the side. However, upon examination of the 2014 results, these treatments were modified. The mowing treatment was discarded because it was deemed to have little potential for weed control. Fomesafen was included as a herbicide. Each herbicide treatment was comprised of one application each of two different herbicides (Table 2.1). Among the four herbicides used, fomesafen and rimsulfuron had greater post-emergent activity on the living mulches, while halosulfuron and metribuzin caused less severe injury. In 2015 and 2016, four herbicide treatments were used, along with three control treatments. The control plots were: 1) control, which was kept weed-free by hand-weeding; 2) untreated living mulch check, with no herbicide applications (except grass herbicides); and 3) weedy check, with no living mulch or herbicide applications (except grass herbicides), or other forms of weed control.

Herbicide applications were made using a pressurized carbon dioxide sprayer, operating between 200 - 240 kPa pressure, at approximately 320 L ha^{-1} spray volume. The spray boom consisted of two flat fan nozzles, with an overall swath of about 1.1 m at an operating height of about 50 cm from the ground. The first herbicide application was typically made in late June, 20 - 25 days after living mulch emergence. The second herbicide application was typically made around the third week of July. Choice of herbicides and application timings must consider the post-harvest intervals, which can be long in vegetable crops. Even though Mountain Fresh is marketed as a determinate tomato variety, three harvests were required in 2015 and 2016, and five in 2014. Harvest typically started in early September and was completed by late September. No distinct termination operation was carried out for the living mulches. Tomato harvest operations caused severe injury to the living mulch stands, and moreover, the dropping temperatures in late September were very effective in arresting growth of the warm-season living mulches; as such, flowering/seed-set of the living mulches was not deemed to be an issue.

Percent living mulch and weed cover, and living mulch height, were measured approximately four times during the season. Biomass and density of living mulch and weeds were measured no earlier than a few days before the beginning of the tomato harvest. Living mulch biomass and density were determined from two randomly chosen 50 cm long lengths of living mulch row, at least 60 cm away from plot edges. These values were then converted to per hectare basis. Weed biomass and density were determined from two randomly chosen 0.25 m^{-2} areas (50 by 50 cm), again at least 60 cm away from the plot edges. Both cover crops and weeds were cut at ground level to estimate aboveground biomass. Weed parameters encompassed both grass and broadleaf weeds. Living mulch and weed biomass were weighed immediately after sampling, and following oven-drying for two weeks at 75 C. Nutrient concentrations in tomato tissue were also determined in 2015 and 2016. For this purpose, at the time of peak flowering, a total of 50 g (fresh) of tomato leaves were sampled from 10 randomly selected plants within the two central rows of each plot. Analyses were done by Dairy One Cooperative, Inc., Ithaca, NY 14850.

During 2016, in the same field, a separate strip of living mulch was planted to inoculated sunnhemp. Sunnhemp seeds were inoculated with a suitable strain of rhizobium bacteria for nitrogen fixation. None of the living mulches were inoculated during any year in the main trials. The purpose of this inoculated sunnhemp strip in 2016 was only to perfunctorily examine the effects of living mulch nitrogen fixation on the competition between tomato, living mulch and weeds. This strip consisted of two treatments: one herbicide treatment and one untreated check, with four replications. All planting and management operations conducted were similar to those used in the main tomato trial described previously. From the two treatments in the inoculated strip, and from its non-inoculated counterparts in the main tomato trial, a second set of tomato leaf samples were collected and subjected to nutrient analyses. At this time, sunnhemp tissue samples were also collected from these treatments. For this purpose, a total of 50 g (fresh) of the top 20 to 25 cm of sunnhemp shoot tissue was harvested from the center of these plots. Sampling was carried out in early September to provide more time for any effects from the inoculation to be seen.

Data analyses: The living mulch (cover, height, density, biomass and tissue nutrient composition), weed (cover, density and biomass) and tomato (yield and tissue nutrient composition) parameters were subjected to analysis of variance (ANOVA) and regression analyses at 5% level of significance. To compare treatment differences, Tukey's HSD test was used. Herbicide treatments were considered as fixed effects. Data across years were not combined for analyses due to very different climatic conditions in 2015 and 2016. Moreover, 2014 was a preliminary trial year where herbicide treatments were different from those used in 2015 and 2016. Statistical analyses were carried out using JMP Pro 12 (2013 SAS Institute Inc., Cary, NC) software.

Results and Discussion

Summer temperatures were below average in 2014. As a result, the warm-season living mulch emergence was delayed, as was initial growth and establishment. Sunnhemp grew with adequate vigor as the season progressed. Sesbania did not establish very well. As a result, sesbania was severely impacted by the herbicide treatments, and these plots had high weed pressure. There was above-average rainfall in 2015, which again hampered the emergence and growth of sesbania. During this year, sunnhemp was not affected. One factor that could have made sesbania so susceptible to the weather could be its smaller seed size. Data were not collected from the sesbania treatments during 2014 or 2015 since the sesbania stands establishment was poor. In 2016, sesbania was not planted for evaluation. Hence, the following discussion is based only on sunnhemp data.

Treatment differences were weak for many of the living mulch and weed parameters in 2015. It is possible that the adequate rainfall moderated the effects of living mulch-weed-crop competition. In 2016, however, treatment effects were more pronounced, and significant relationships were observed between living mulch, weed and crop parameters. Major weeds in the experimental plots were Powell amaranth (*Amaranthus powellii* S. Watson), shepherd's purse [*Capsella bursa-pastoris* (L.) Medic.] lambsquarters (*Chenopodium album* L.), hairy galinsoga (*Galinsoga quadriradiata* Cav.), common purslane (*Portulaca oleracea* L.), and eastern black nightshade (*Solanum ptycanthum* Dunal).

Tomato Yield. In 2014, tomato yield from the various treatments differed significantly ($p = 0.0001$) (Table 2.2). Tomato yields from the higher rates of metribuzin and rimsulfuron were 73 and 76 tons ha^{-1}, respectively, compared with 66 tons ha^{-1} from the hand-weeded control. In 2015, the yield in the control plot was comparable to the yield from all herbicide treatments, except the metribuzin + halosulfuron treatment, which was lower (Table 2.3). In 2016, tomato yield in the control plots was significantly higher than from all the other treatments ($p = 0.0001$), including all the herbicide treatments (Table 2.4). Incidence of early blight (*Alternaria solani*) was high in 2015 since it was a very wet year. Under such conditions, the presence of the living mulch could have reduced tomato yield by increasing the susceptibility of the tomato plants to disease by reducing air circulation and increasing leaf drying time. During the same year, however, there was a strong positive correlation between tomato yield and living mulch biomass ($p = 0.0167$) (Figure 2.1). Hence, the presence of the living mulch, or its vigor, did not cause tomato yield reductions. This is a desirable outcome since sustainability benefits of the living mulch can potentially be maximized without adversely affecting crop yield. In earlier studies on living mulch systems, results had been less promising. Crop yields were higher when greater quantities of herbicides were used to suppress living mulch vigor. For example, in a corn crop grown in a crownvetch sod, up to 68% reduction in crownvetch biomass and up to 66% reduction in its cover was required to achieve maximum corn yield (Linscott and Hagin 1975).

In another study of a vegetable living mulch system, where the living mulch was managed by mowing, the combined living mulch and weed biomass caused as much or greater reductions in broccoli yield in the weedy check plots (Chase and Mbuya 2008).

Our results from 2015 did not follow this trend, that is, compared to 12 tons ha^{-1} tomato yield from the weedy check plots, tomato yield from the herbicide treatment plots ranged from 16 to 27 tons ha^{-1} (Table 2.3). Even when the competition from the inter-row space was considered by combining living mulch and weed biomass, there was no correlation with tomato yield ($p = 0.086$). Since the total inter-row biomass was similar between the Chase and Mbuya (2008) study and ours, the disparity in the outcomes with regard to tomato yield was perhaps due to greater spacing between tomato and living mulch rows used in our trials.

In 2015, the best of treatments in terms of tomato yield were almost identical to the poorest treatments in terms of weed biomass (Figure 2.2), with an overall marginally significant negative relationship between tomato yield and weed biomass ($p = 0.074$). These results from 2015 suggest that the living mulch planting and management strategies were effective in minimizing living mulch-tomato competition. Furthermore, tomato yield reductions were probably caused by weeds alone, and not the living mulch. Living mulch biomass in the herbicide treatments ranged from 2.1 to 2.8 tons ha^{-1} (Table 2.3). This level of biomass production by the living mulch and the positive relationship between tomato yield and living mulch biomass in 2015, contrasts with the negative relationship that has been typically reported from living mulch studies. For example, in a corn crop, a corresponding yield loss of 77% was reported in order to obtain a living mulch biomass of 2.7 tons ha^{-1} (Linscott and Hagin 1975).

In 2016, although weed biomass in the weedy check was approximately 9 tons ha^{-1}, both weed biomass and living mulch biomass from the herbicide treatments were in the same range as recorded in 2015 (Table 2.3; Table 2.4). However, unlike in 2015, tomato yield in 2016 was negatively correlated to both living mulch ($p = 0.0463$) and weed ($p = 0.003$) biomass. There was a severe, extended drought during the 2016 growing season, and even though irrigation was provided, competition for water likely caused this outcome. Hence, the positive relationship between tomato yield and living mulch biomass in 2015 was likely because of the above-average rainfall received during that year. Effects of soil moisture conditions on the outcome of living mulch systems have been previously documented; where in a wet year, there was no reduction in crop yields due to competition from living mulches or weeds (Echtenkamp and Moomaw 1989). In the same study, when soil conditions were dry, the chewings fescue [*Festuca rubra* L. ssp. *fallax* (Thuill.) Nyman] and ladino clover (*Trifolium repens* L.) living mulches competed well with weeds, but also with the corn crop. Influence of moisture availability on the outcome of living mulch systems has also been observed in tropical cotton (Bhaskar et al. xxxx). In a series of six field trials at four locations, non-chemical management of living mulch systems were evaluated using five different living mulch species. In 2012, which was a dry year, there was an overall negative relationship between cotton yield and living mulch biomass. However, in 2013, which was a wet year, the relationship between cotton yield and living mulch biomass was positive.

Tomato yield was negatively impacted by increasing living mulch biomass in 2014 also ($p < 0.0001$) (Figure 2.3). The lowest tomato yield from herbicide treatments (52 tons ha^{-1}) was obtained from the halosulfuron treatment, which produced the largest amount of living mulch biomass (1.36 tons ha^{-1}) (Table 2.2). Excessive living mulch vigor has been previously linked to considerable crop yield losses (Hartwig 1976). Amount of precipitation however, was not a likely cause for this loss in tomato yield since the 2014 summer was normal in this regard, albeit much colder. Moreover, on average, tomato yield from the lower and higher rates of metribuzin and the higher rate of rimsulfuron were 67, 73 and 76 tons ha^{-1}, compared to 66 tons ha^{-1} from the control (Table 2.2). This is further indication that the treatments were effective in minimizing living mulch-cash crop competition.

Weed biomass was not measured in 2014, but average weed cover had an unexpected positive relationship with living mulch biomass ($p = 0.0035$) (Figure 2.3). So, weed pressure was higher in treatment plots with more vigorous living mulches. Therefore, weeds, and not living mulches, were probably responsible for tomato yield reductions, although a negative relationship between living mulch biomass and tomato yield was created due to the positive association of living mulch biomass with weed pressure. The negative correlation ($p = 0.003$) between tomato yield and weed cover during this year (Figure 2.3) provided support for this reasoning. Such varying effects of living mulch and weeds on crop yield are possible. In an earlier study in corn, two different living mulches, even though they produced similar biomass, were reported to compete with the crop at different degrees (Echtenkamp and Moomaw 1989). This was attributed to contrasting growth habit. In our trials, differences in location (within the inter-row) and growth of living mulches and weeds might be responsible for their contrasting impacts on tomato yield. The distance between the living mulch and tomato rows, along with the erect stature of sunnhemp plants, could have minimized competition with and disturbance to, the tomato crop. On the other hand, presence of weeds close to or within the tomato row, and their comparatively higher degree of interference with the tomato canopy, could be responsible for the stronger (negative) associations between weeds and the tomato crop.

The anomalous positive relationship between weed cover and living mulch biomass is perhaps because the living mulch was not able to suppress weeds adequately by itself, without sufficient assistance from the herbicide applications. It is possible that the herbicide applications in 2014, which were different from those used in 2015 and 2016, were neither efficacious enough to adequately aid the living mulch in weed suppression, nor diverse enough to provide a desirable balance between living mulch vigor and weed control. Such increase in weed pressure in weak living mulch stands has been reported before, when herbicide applications fail to provide adequate weed suppression (Hartwig and Hoffman 1975). Vrabel et al. (1980) also reported that the living mulch that produced the maximum biomass in their experiment also had the highest weed pressure.

In 2014, herbicide applications that had greater post-emergent activity provided better weed suppression. But, although not significant, they also caused greater reductions in living mulch biomass (Table 2.2). In these treatments, tomato yield was not adversely affected, relative to the control. Herbicide treatments that had weaker post-emergence activity had the greatest living mulch and weed biomass, and the lowest tomato yields. In a year like 2014 where water was adequate, the living mulch growth probably did not negatively affect tomato yield, but the increased weed pressure was enough to reduce tomato yield (Figure 2.3). In 2015, the herbicide treatments were modified to affect weeds more effectively. The modified herbicide treatments were also expected to injure weeds disproportionately more compared with the living mulch. The results from 2015 indicate that these changes to the herbicide treatments were effective in preventing any such correlation between living mulch biomass and weed biomass ($p = 0.41$).

Effect of Living Mulch Height. In 2016, the lowest tomato yield (29 tons ha^{-1}) was obtained from the untreated living mulch check (Table 2.4). This was numerically even lower (statistically comparable) than the weedy check (37 tons ha^{-1}). Weed biomass from the untreated check (2.1 tons ha^{-1}) however, was significantly lower than from the weedy check (9 tons ha^{-1}), and comparable to weed biomass from the other treatments (0.3 to 2 tons ha^{-1}) (Table 2.4). Living mulch biomass from the untreated check (2.8 tons ha^{-1}) also did not differ from two other treatments (2.5 and 1.4 tons ha^{-1} in metribuzin + halosulfuron and metribuzin + rimsulfuron, respectively), which recorded 59 and 66 tons ha^{-1} tomato yield, respectively. Increased weed pressure or increased competition for water were probably not responsible for this low tomato yield from the untreated living mulch check. One parameter that stood out in this treatment was living mulch height (Table 2.4; Figure 2.4). At 116 cm, living mulch in the untreated check was taller than living mulch in all other treatments ($p = 0.0001$). Compared with the untreated check, herbicide treatments reduced living mulch height by 16 to 49 cm. The rimsulfuron + metribuzin treatment had weed biomass (1.4 tons ha^{-1}) similar to the untreated check. But, living mulch height was 75 cm and tomato yield was 60 tons ha^{-1} (Table 2.4). In addition, there was a strong negative relationship ($p = 0.0005$) between tomato yield and living mulch height in 2016. Based on these results, reduction in living mulch height was a very important function of the herbicide treatments.

When, in the statistical model, the 2016 tomato yield was adjusted for differences in weed biomass and living mulch biomass between treatments, the projected tomato yields were not very different from the actual tomato yields. However, when tomato yield was adjusted for living mulch height, a 44% yield increase was projected for the untreated living mulch check. Such negative relationships between tomato yield and living mulch height was not evident in 2014 ($p = 0.67$) or 2015 ($p = 0.1$). This was despite the living mulch in the untreated check being taller than living mulch in most of the other treatments (Table 2.3). Moreover, tomato yield from the untreated check was only slightly greater than from the weedy check (Table 2.3). Since there were strong positive relationships between living mulch height and living mulch biomass in 2014 ($p = 0.0484$), 2015 ($p < 0.0001$) and 2016 ($p < 0.0001$), it could be the combination of both increased water stress and shading that reduced tomato yield in tall living mulch plots during the dry summer of 2016. Whereas, in case of 2014 and 2015, perhaps only the shade factor caused a problem, and was likely not remarkable enough to decrease yields.

Height of the living mulch was measured four times during the growing season (Figure 2.4), and the average of these heights, in 2016, were significantly lower in rimsulfuron + metribuzin (40 cm), than metribuzin + rimsulfuron (54 cm) (Table 2.4). Reducing living mulch height was an important function of herbicide applications- to minimize shading of the tomato crop. However, tomato yield from both these treatments were similar in 2016. This could partly be because the rimsulfuron + metribuzin treatment could not suppress living mulch height for long, and by mid-August, living mulch height from both these treatments were similar. But, what most likely affected the potential yield benefits from reduced living mulch height (in the rimsulfuron +

metribuzin treatment) was increased weed pressure. Weed biomass was more than three times higher in rimsulfuron + metribuzin, relative to metribuzin + rimsulfuron (Table 2.4). Tomato yield had a negative correlation (marginally in 2015) with weed biomass during both 2015 and 2016 ($p = 0.074$; $p = 0.003$, respectively). After the herbicide treatments were modified following the 2014 trial year, however, there was no correlation between weed biomass and living mulch height ($p = 0.71$ (2015); $p = 0.75$ (2016)). This suggests that, while the rimsulfuron + metribuzin and fomesafen + metribuzin treatments reduced living mulch height more than the other treatments, these reductions in living mulch height were not necessarily associated with increased weed suppression.

Living Mulch Height, Cover and Density. Living mulch height in the metribuzin + halosulfuron treatment (105 cm) was similar to the untreated living mulch check (114 cm) in 2015 (Table 2.3). All other herbicide treatments (74 to 85 cm) reduced living mulch height. At the end of the season (early October), living mulch in metribuzin + halosulfuron was 131 cm tall, while living mulch in the untreated check was only 121 cm (Figure 2.5). In this herbicide treatment, living mulch biomass was 2.8 tons ha^{-1}, compared with 2.7 tons ha^{-1} from the untreated check. In metribuzin + halosulfuron, the herbicide applications did not injure the living mulch too much, but probably affected the weeds (which were smaller). Compared with the untreated check, this could have provided the living mulch in metribuzin + halosulfuron with a less competitive environment, resulting in increased growth.

In 2016 also, living mulch in metribuzin + halosulfuron (100 cm) was taller than living mulch in the other herbicide treatments, which had similar living mulch heights (67 to 81 cm) (Table 2.4; Figure 2.4). As discussed previously, reduction in living mulch height is important for prevention of crop yield losses, and an important function of the herbicide applications. An earlier study had reported 15% reduction in crop yield in a 6 to 8 cm tall chewings fescue living mulch, but a 46% yield loss in a taller rye (*Secale cereale* L.) plus oats (*Avena sativa* L.) plus vetch (*Vicia villosa* Roth) living mulch (Echtenkamp and Moomaw 1989). However, this effect of herbicide applications on the living mulch must not cause any remarkable losses in living mulch cover or density.

In 2016, living mulch cover in the metribuzin + halosulfuron (85%) and metribuzin + rimsulfuron (76%) treatments were similar to each other and to the untreated living mulch check (82%), but higher than the other herbicide treatments (21 to 42%). Average living mulch cover in the metribuzin + rimsulfuron treatment (60%) was similar to that in the untreated check (56%) in 2015 also (Table 2.3). But the treatments did not differ in terms of living mulch density in either 2015 or 2016 ($p = 0.38$ and $p = 0.75$, respectively). This indicates that the metribuzin + rimsulfuron treatment can reduce living mulch height without compromising soil cover or density. In living mulch systems, ability of the management techniques to maintain living mulch cover and density (as in case of metribuzin + rimsulfuron in 2016), or even improve living mulch vigor by minimizing competition from weeds (as in case of metribuzin + halosulfuron in 2015) is consequential. This need for good soil cover by living mulches has been highlighted in earlier research (Hoffman and Hartwig 1975).

There was no effect of treatments on living mulch density in 2015 ($p = 0.38$) or in 2016 ($p = 0.75$) (Table 2.3; Table 2.4). Absence of differences in living mulch density between treatments means that the herbicide applications did not cause mortality among the living mulch plants, which was a desirable outcome. Gaps in the living mulch stand, even small areas, can quickly become epicenters for weed outbreak. When herbicide injury on living mulches are too severe, rapid establishment of broadleaf weeds can occur (Hughes and Sweet 1979). When living mulch stand is dense, weed suppression is generally improved (Brainard and Bellinder 2004). Probably because the treatments were similar in terms of living mulch density, there was no evidence of weed biomass ($p = 0.36$ and $p = 0.1$, respectively) or weed density ($p = 0.94$ and $p = 0.5$, respectively) being impacted by this parameter.

Weed Suppression. During both 2015 and 2016, there was no correlation between living mulch biomass and weed biomass ($p = 0.36$ and $p = 0.75$, respectively). This suggests that the herbicide applications played an important role in weed control. Weed biomass in 2015 ranged from 0.4 to 1.3 tons ha^{-1} and weed biomass from the weedy check was 2.6 tons ha^{-1} (Table 2.3). Hence, all herbicide treatments suppressed weeds considerably. But, in terms of living mulch biomass, the untreated living mulch recorded 2.7 tons ha^{-1}, which was not very different from the herbicide treatments. So, as hypothesized, the herbicide applications were capable of affecting weeds disproportionately more. The difference in living mulch and weed size at the time of the first herbicide application could be responsible for this outcome. In our trials, the living mulch generally emerged earlier than the weeds, and was approximately 20 cm tall at the time of weed emergence. So, the first herbicide application likely injured the weeds more than the living mulches. And due to this initial advantage, the living mulches were still larger than the weeds at the time of the second herbicide application, which also probably affected the weeds more. Alternatively, herbicides that the living mulch expresses some tolerance to can be used for the first application so that weeds are injured disproportionately more. When a greater number of herbicides are registered for use in the crop, there are greater chances of identifying such herbicides.

Weed cover at the beginning of tomato harvest decreased with increasing living mulch density during both 2015 and 2016 ($p = 0.0017$ and $p = 0.031$, respectively). But, in 2015, there was no effect of treatments on weed biomass ($p = 0.55$) or weed density ($p = 0.3$) (Table 2.3). This indicates that the treatments did not cause mortality of weeds, or stunt their growth in 2015. However, the negative correlation between weed cover and living mulch density suggests that weeds in denser living mulch stands likely grew tall and erect, while weeds in living mulch stands with lower density were more likely to be prostrate with spreading canopy. This is consistent with field observations where lambsquarters and pigweed were more prominent in denser living mulch stands, while hairy galinsoga and nightshade were more prominent in the weedy check and in living mulch stands with lower density.

In 2016 however, all the herbicide treatments had lower weed density ($p = 0.0016$) and lower weed biomass ($p = 0.0001$) than the weedy check (Table 2.4). Regarding both these parameters, all the herbicide treatments were similar to each other. However, the untreated living mulch check was similar to both the weedy check and the herbicide treatments in case of weed density, but lower than the weedy check and similar to the herbicide treatments in case of weed biomass (Table 2.4). Based on this observation, perhaps living mulches need herbicides to reduce weed density, but may reduce weed biomass by itself in a dry year. Since living mulch biomass and density were similar during both years, the dry conditions in 2016, compared with the wet conditions in 2015, probably exposed and enhanced the competitive effects of living mulch on weeds.

Effect of Order of Herbicide Application. Herbicide treatments with a first application of metribuzin demonstrated better weed control (Figure 2.4). In 2016, the metribuzin + rimsulfuron (0.44 tons ha^{-1}) and metribuzin + halosulfuron (0.3 tons ha^{-1}) treatments reduced weed biomass by 95% and 97%, respectively, compared with the weedy check (9 tons ha^{-1}) (Table 2.4). The metribuzin + halosulfuron treatment, which had the lowest weed biomass, also had the highest living mulch biomass (2.5 tons ha^{-1}), which was only 10% lower than weed biomass in the untreated living mulch check. On the other hand, highest weed biomass among herbicide treatments (2 tons ha^{-1}) was recorded in fomesafen + metribuzin, which also had the lowest living mulch biomass (0.7 tons ha^{-1}). These results are in agreement with some earlier reports of living mulches improving the efficacy of herbicide applications in weed control (Hartwig 1977). Hughes and Sweet (1979) and Echtenkamp and Moomaw (1989) also reported increase in weed pressure when living mulch vigor and cover were affected too severely by herbicides. The same researchers also reported that inability of herbicide applications to suppress living mulches led to yield losses in vegetable crops. In 2016, however, the considerable disparity in living mulch and weed biomass between metribuzin + halosulfuron and fomesafen + metribuzin was not reflected in tomato yield, which was similar among all the herbicide treatments (Table 2.4). The reason for this is not clear, but these variations in results between our study, and the Echtenkamp and Moomaw (1989) and Hughes and

Sweet (1979) studies could be due to differences in herbicide application strategies and differences in planting geometry of vegetables and living mulch.

In 2016, the untreated living mulch check, which had a weed biomass of 2.1 tons ha^{-1} reduced weed biomass by 76%, compared to the weedy check (Table 2.4). Overall, the herbicide treatments reduced weed biomass by 78 to 97%. This means that the addition of herbicide applications to the living mulch increased weed suppression by up to 21%. Compared with the untreated check, weed control was approximately 5 and 7 times greater in the metribuzin + rimsulfuron and metribuzin + halosulfuron treatments, respectively, in 2016. During the same year, metribuzin + rimsulfuron (9%) and metribuzin + halosulfuron (4%) treatments reduced weed cover by 91 to 96%, compared with the weedy check (98%). Without herbicide applications, the untreated check reduced weed cover by 81%. This increase in weed suppression with the addition of herbicide applications (seven and five times, respectively, in case of weed biomass and weed cover) may be noteworthy in the context of weed seed production. Compared with 39% in mid-July, the untreated check reduced weed cover to 19% by mid-August. The herbicide treatments reduced weed cover from 22 - 69% in mid-July to 4 - 35%, respectively, in mid-August (Figure 2.4).

In 2015, all herbicide treatments reduced weed biomass compared with the untreated living mulch check, although not significantly (Table 2.3). Lowest weed biomass were recorded from the rimsulfuron + metribuzin (0.4 tons ha^{-1}) and metribuzin + rimsulfuron (0.7 tons ha^{-1}) treatments. Weed biomass reduction in these treatments, compared with the weedy check (2.6 tons ha^{-1}) was 84% and 75%, respectively. By itself, the living mulch stand (untreated check), reduced weed biomass by 22%. This extent of weed suppression by living mulch alone and combinations of living mulches with herbicides was similar to data from 2016. Weed cover estimated during mid-August indicated that only the (two) herbicide treatments with a first application of metribuzin reduced weed cover more than the untreated living mulch check. Both these herbicide treatments reduced weed cover by 57%.

Herbicide Effects on Living Mulch. Combinations of herbicides have been previously used for living mulch suppression (Cardina and Hartwig 1980; Linscott and Hagin 1975; Hartwig 1976; Hartwig 1977). But, they were usually applied in single applications. When the herbicide treatments were designed in our experiments, it was expected that an early/first application of a herbicide with greater post-emergence activity would result in higher crop yields due to more effective reduction in living mulch-cash crop competition. Such a herbicide application will not only cause severe injury to the (young) living mulch, but will also result in a longer recovery time. The degree of living mulch mortality will also be higher. This would provide a less competitive environment for the crop during its early stages of growth, thereby potentially increasing crop yield.

However, weed suppressive ability would be compromised here due to 1) the severe and extended loss in living mulch vigor and 2) poor residual activity of the primarily post-emergent herbicide used. On the other hand, first application of a primarily pre-emergent herbicide like metribuzin will not affect the living mulch too severely, prompting faster recovery from herbicide injury. There would also be the additional benefit of residual soil activity against early weed emergence and establishment. Living mulch mortality will also be minimized or eliminated. The disadvantage to this was expected to be greater living mulch-cash crop competition throughout the growing season, leading to a potential decrease in crop yield. Following an application of metribuzin, a second application of a primarily post-emergent herbicide is also likely to have diminished effects on the living mulch due to its larger size at the time of the second application. As such, this was also expected to result in much larger living mulch plants at the end of the season.

Regarding the living mulch, these hypotheses were confirmed both in 2015 and in 2016. The differences between these two sets of treatments however, were more pronounced during 2016 (Figure 2.4; Figure 2.5). During this year, in the metribuzin + halosulfuron and metribuzin + rimsulfuron treatments, living mulch cover, height, density and biomass, were 94 and 85%, 100 and 81 cm, 146 and 143 plants m^{-2}, and 2.5 and 1.4 tons ha^{-1}, respectively (Table 2.4). These parameters were 78 and 40%, 75 and 67 cm, 133 and 121 plants m^{-2}, and 1.3 and 0.7 tons ha^{-1}, respectively, in the rimsulfuron + metribuzin and fomesafen + metribuzin treatments, respectively. The greater disparity between these sets of treatments in 2016 could be due to increased stress on the living mulch from drought conditions, which adversely affected recovery from herbicide applications. Lack of any remarkable differences in living mulch biomass between the two sets of treatments in 2015 was most likely due to abundant rainfall, which mitigated these differences and aided in quicker living mulch recovery.

Nutrient Composition of Plant tissue. In 2016, living mulches also had an indirect adverse effect on the tomato crop due to drought conditions. There was a negative correlation between living mulch biomass and the calcium concentration in tomato leaf tissue ($p = 0.016$). As vigorous living mulches exacerbated the effects of drought through increased soil water removal, it could have made uptake of calcium more difficult for the tomato crop. This calcium deficiency caused yield losses from the blossom end rot disorder.

Effects of treatments were observed on the concentration of nutrients in tomato tissue (Table 2.5). However, all effects were not consistent across both 2015 and 2016. In 2015 or 2016, the nutrient composition of tomato tissue did not exhibit many consistent, remarkable trends with living mulch or weed parameters. In 2015, nitrogen ($p = 0.02$) and phosphorous ($p = 0.032$) concentrations in tomato tissue were negatively correlated to living mulch biomass, whereas, potassium ($p = 0.018$) concentration had a positive relationship. In 2016, the concentrations of these nutrients in tomato tissue had no relationship with living mulch biomass. A positive relationship between living mulch height and potassium ($p = 0.02$) was observed. During this year also, there was a strong positive correlation between living mulch height and living mulch biomass ($p = 0.068$). So, it is possible that the strong association between living mulch height and living mulch biomass during both years might have caused the relationships between the nutrients and living mulch height. Or, living mulch biomass and living mulch height both could have had an impact on the nutrient composition of the tomato crop.

Although sunnhemp (and sesbania) is a legume, it was not inoculated in any of the trial years. As a result, nodulation was almost absent. The assumption was that this would make the living mulches more effective in weed suppression by making the inter-row space more competitive for nitrogen, and reduce leaching of nitrogen fertilizers. In 2016, supplementary plots were established to perfunctorily explore the outcomes of legume living mulch inoculation (Table 1, Appendix; Table 2, Appendix). For this purpose, four replications of the untreated check and the rimsulfuron + metribuzin treatments were established separately using inoculated sunnhemp. During this year, sunnhemp tissue, collected at the same time as the tomato tissue, was also analyzed for nutrient composition (Table 3, Appendix). Analyses of results from these trial plots, along with its non-inoculated counterparts (non-inoculated untreated check and non-inoculated rimsulfuron + metribuzin treatment), and the control and weedy check, generated some interesting preliminary results.

In case of both the untreated check and rimsulfuron + metribuzin, inoculation of the living mulch reduced tomato yields (Table 1, Appendix). Tomato yield from the inoculated rimsulfuron + metribuzin treatment (44 tons ha^{-1}) was statistically similar to all other herbicide treatments with non-inoculated sunnhemp, but tomato yield from these latter treatments ranged from 58 to 66 tons ha^{-1}. Tomato yield from the untreated inoculated living mulch (20 tons ha^{-1}) was the lowest among all inoculated and non-inoculated sunnhemp treatments, including the weedy check.

For a late-season examination of the impact of inoculation on the nutrient status of tomato and sunnhemp tissue, a second set of samples from both (inoculated and non-inoculated) untreated checks and rimsulfuron + metribuzin treatments were collected approximately three weeks after the collection which was made at the time of peak tomato flowering (Table 2, Appendix; Table 3 Appendix). Interestingly, even though nitrogen concentration in the sunnhemp tissue at the time of peak tomato flowering, was higher in the inoculated plants (3.62 and 3.61% in the untreated check and rimsulfuron + metribuzin, respectively), relative to their non-inoculated counterparts (2.94 and 2.45%, respectively) ($p = 0.0001$), the concentration of nitrogen in the tomato tissue was similar in both inoculated (3.35 and 3.35%, respectively) and non-inoculated (3.36 and 3.51%, respectively) treatments. Later in the season, there was also a positive correlation between sunnhemp biomass and nitrogen concentration in sunnhemp tissue ($p = 0.026$). It is possible that excessive soil moisture removal by the more vigorous inoculated sunnhemp prevented any effects from increased nitrogen availability from being revealed.

Later in the season, nitrogen concentration in the tissue of inoculated sunnhemp remained approximately same, but nitrogen concentration in the non-inoculated sunnhemp decreased to approximately 2% in both treatments (Table 3, Appendix). At this time, nitrogen concentration in tomato tissue decreased to approximately 2.7% in these non-inoculated treatments (Table 2, Appendix). This was similar to the inoculated rimsulfuron + metribuzin treatment (3.2%), but lower ($p = 0.013$) than the inoculated untreated check (3.8%). So, the first sampling indicated that the tomato crop was not benefitting from the nitrogen that was being fixed by the inoculated sunnhemp. Results from the second sampling indicate that the tomato crop did benefit from this increased nitrogen availability. Therefore, as a result of 1) benefitting from the increased nitrogen availability too late in the season, or 2) the dry conditions, likely made more severe by the more vigorous inoculated sunnhemp, or 3) due to excessive shading by the larger inoculated sunnhemp, the tomato crops in the inoculated-sunnhemp plots were probably not able to use this extra nitrogen to increase yields. On the contrary, the drawbacks from inoculation far outweighed the merits.

The following discussion is based on the results from the second set of tissue sample collection. When the two inoculated treatments, and their non-inoculated counterparts were considered, nitrogen concentration in the tomato tissue was positively correlated to both sunnhemp biomass ($p = 0.0031$) and nitrogen concentration of sunnhemp tissue ($p = 0.015$). From an earlier study in sweet corn, Vrabel et al. (1981) had reported a 50% increase in nitrogen concentration of corn tissue when corn was planted with legume living mulches, compared with corn planted without living mulches. Potassium concentration in the tomato tissue was positively correlated to sunnhemp biomass ($p < 0.0001$). However, this relationship seemed to be restricted to only the amount of living mulch biomass, and did not depend on whether it was inoculated.

Tomato tissue from the inoculated untreated check had the highest concentrations of many major nutrients (nitrogen, phosphorous, potassium and iron) (Table 2, Appendix). And, living mulch biomass from this the inoculated untreated check was higher than from all other treatments ($p = 0.0012$). However, the relationship between tomato yield and living mulch biomass was negative ($p = 0.0008$). So, although there was no indication of competition between living mulch and tomato for nitrogen and other nutrients, and although such competition was slightly mitigated by inoculation of the living mulch, there were other factors that caused vigorous living mulch stands to adversely affect tomato yield. In case of all these nutrients, the benefits from their higher concentrations were probably nullified and superseded by a combination of 1) excessive living mulch height, which caused shading of the tomato canopy, and 2) living mulch-tomato competition for water during the dry summer of 2016. Inoculation of the living mulch also did not have any impact on weed cover ($p = 0.67$) or weed biomass ($p = 0.43$).

In an earlier living mulch study in cabbage, addition of supplemental nitrogen to account for the living mulch led to increased growth of both living mulch and weeds, and consequent reductions in crop yield from competition for light, and to a lesser extent, water (Brainard et al. 2004). The living mulch was unacceptably tall in the inoculated untreated check-141 cm before tomato harvest, with an end-of-season dry matter production of 4.7 tons ha^{-1} (Table 1, Appendix). Compared to this, the rimsulfuron + metribuzin herbicide combination, reduced living mulch height by 40% (86 cm).

Tomato Canopy Width. In 2016 alone, width of the tomato canopy was measured before harvest to cursorily examine if the tomato plants were benefitting from the herbicide applications by using this period of arrest in living mulch vigor to expand its own canopy. As expected, average canopy width was highest in the control (101 cm) (Table 4, Appendix). All herbicide treatments (74 to 81 cm) were similar to each other and to the control in this respect, except fomesafen + metribuzin (74 cm), which was lower than the control. Since, the canopy width in the herbicide treatments were only 20 to 25 cm narrower, relative to the control (in a total space of 122 cm), the herbicide treatments probably facilitated the expansion of the tomato canopy by adequately curbing living mulch vigor. Compared to the untreated check (60 cm), herbicide treatments had 23 to 35% wider tomato canopy. The weedy check had the narrowest tomato canopy, only 31 cm wide. Canopy width of the tomato crop had no correlation ($p = 0.35$) with living mulch cover, but had a strong negative relationship ($p < 0.0001$) with weed cover (even not considering the weedy check ($p = 0.04$)). Similarly, while living mulch biomass did not affect tomato canopy width ($p = 0.61$), weed biomass did have a negative effect (p

< 0.0001; $p = 0.0007$ excluding the weedy check). This demonstrates the feasibility of preventing living mulch-crop competition through strategic planting and management techniques. Living mulch height also had a negative impact ($p = 0.041$) on canopy width. As expected, canopy width was positively correlated with both tomato yield ($p < 0.0001$) and tomato tissue nitrogen concentration ($p = 0.0012$).

Implementation of this living mulch-herbicide cropping system revealed many constraints, but this is still a relatively nascent science and more research is required to establish broad guidelines. Along with this, more focused evaluations are equally important in order to consider crop, climate, planting geometry, living mulch species, herbicide type, herbicide application rate, herbicide application timing, weed species, specific sustainability issues, etc. However, our experiments demonstrated that such a living mulch-herbicide system is a sustainability tool worth considering in fresh market field tomato. Even though yield is a very important criterion, in the future small compromises in crop yield must be acceptable for the overall improvement in soil and agro-ecosystem sustainability.

In addition to the several soil conserving properties through such a cropping system, tillage was reduced since no inter-row tillage operations were carried out after the living mulch and tomato were planted. Pre-emergent herbicides were also not used in our trials. There was no additional input of fertilizers to compensate for the living mulch. This, besides putting no extra economic or environmental stress on the production system (especially regarding nitrogen), also helps to improve the longer-term efficiency of fertilizers by tying them up in the living mulch tissue. Once techniques are developed to adequately limit vigor of inoculated legume living mulches, they can be useful in reducing the input of synthetic nitrogen fertilizers.

In summary, the results elucidating the competitive interactions between living mulch, weeds and the crop, demonstrated that 1) optimum soil moisture is required to prevent living mulches from adversely affecting crop yield, 2) herbicide applications may be essential in obtaining adequate weed control in living mulch systems and 3) in the presence of a combination of living mulch and weeds, crop yield is capable of being affected only by the weeds. In a cropping system, there are many factors that can be manipulated so that herbicide input is reduced and their applications target weeds disproportionately more than the living mulch. Once these factors are established, it is important that the herbicide rates are based on achieving adequate weed control, and not on achieving a target living mulch biomass. This is because even vigorous living mulch stands are relatively unreliable in the context of crop yield. The positive relationship between tomato yield and living mulch biomass in 2015 demonstrated the potential of such reduced-rate herbicide combinations for management of living mulches, and for overall herbicide reduction. It is also a clear indication of the strong positive association that is possible between cash crops and living mulches.

Acknowledgements

We thank Peter Putriment, Rebecca Wilk, Steve McKay, Rick Randolph and Ethan Tilebein for their assistance in the experiment. This project was partly supported by a grant from the Northeastern Sustainable Agriculture Research and Education (NE-SARE).

Literature cited

Akobundu IO, Sweet RD, Duke WB, Minotti PL (1975) Weed response to atrazine and alachlor combinations at low rates. Weed Sci 23:67–70

Brainard DC, Bellinder RR (2004) Weed suppression in a broccoli–winter rye intercropping system. Weed Sci 52:281–290

Brainard DC, Bellinder RR, Miller AJ (2004) Cultivation and interseeding for weed control in transplanted cabbage. Weed Technol 18:704–710

Cardina J, Hartwig NL (1980) Suppression of crownvetch for no-tillage corn. Pages 53–58 *in* Proceedings of the 34th Northeastern Weed Science Society Meeting

Chase CA, Mbuya OS (2008) Greater interference from living mulches than weeds in organic broccoli production. Weed Technol 22:280–285

Currey WL, Cole RH (1966) Comparisons of atrazine, atrazine-surfactant and atrazine-oil mixtures. Pages 297–300 *in* Proceedings of the 20th Northeastern Weed Science Society Meeting

Dickerson CTJ, Sweet RD (1968) Atrazine, oil, and 2,4-D for postemergence weed control. Pages 64–75 *in* Proceedings of the 22nd Northeastern Weed Science Society Meeting

Echtenkamp GW, Moomaw RS (1989) No-till corn production in a living mulch system. Weed Technol 3:261–266

Elkins DM, George JD, Birchett GE (1982) No-till soybeans in forage grass sod. Agron J 74:359–363

Elkins DM, Vandeventer JW, Kapusta G, Anderson MR (1979) No-tillage maize production in chemically suppressed grass sod. Agron J 71:101–105

Hall K, Hartwig NL, Hoffman LD (1984) Cyanazine losses in runoff from no-tillage corn in “living” and dead mulches vs. unmulched, conventional tillage. J Environ Qual 13:105–110

Hamill AS, Zhang J (1995) Herbicide reduction in metribuzin-based weed control programs in corn. Can J Plant Sci 75:927–933

Hartwig NL (1976) Legume suppression for double cropped no-tillage corn in crownvetch and birdsfoot trefoil removed for haylage. Pages 82–85 *in* Proceedings of the 30th Northeastern Weed Science Society Meeting

Hartwig NL (1977) Nutsedge control in no-tillage corn with and without a crownvetch cover crop. Pages 20–23 *in* Proceedings of the 31st Northeastern Weed Science Society Meeting

Hartwig NL, Hoffman LD (1975) Suppression of perennial legume and grass cover crops for no-tillage corn. Pages 82–88 *in* Proceedings of the 29th Northeastern Weed Science Society Meeting

Hoffman LD, Hartwig NL (1975) Perennial soil conserving cover crops for no-till corn. Page 89 *in* Proceedings of the 29th Northeastern Weed Science Society Meeting

Hughes BJ, Sweet RD (1979) Living mulch: A preliminary report on grassy cover crops interplanted with vegetables. Page 109 *in* Proceedings of the 33rd Northeastern Weed Science Society Meeting

Linscott DL, Hagin RD (1975) Potential for no-tillage corn in crownvetch sods. Page 81 *in* Proceedings of the 29th Northeastern Weed Science Society Meeting

Liu LC, Ilnicki RD, Regan JB, Visinski EJ (1966) Naphthenic and paraffinic oils as adjuvants in atrazine and linuron sprays for weed control in corn. Pages 309–316 *in* Proceedings of the 20th Northeastern Weed Science Society Meeting

Moomaw RS, Martin AR (1976) Herbicides for no-tillage corn in alfalfa sod. Weed Sci 24:449–453

Peters RA, Currey WL (1970) Influence of sod species in no-tillage corn production. Pages 421–425 *in* Proceedings of the 24th Northeastern Weed Science Society Meeting

Robertson WK, Lundy HW, Prine GM, Currey WL (1976) Planting corn in sod and small grain residues with minimum tillage. Agron J 68:271–274

Shelby PPJ, Coffey DL, Rhodes GNJ, Jeffery LS (1988) Tomato production and weed control in no-tillage versus conventional tillage. J Am Soc Hortic Sci 113:675–678

Thomas GW, Blevins RL, Phillips RE, McMahon RL (1973) Effect of a killed sod mulch on nitrate movement and corn yield. Agron J 65:736–739

Vrabel TE, Minotti PL, Sweet RD (1980) Seeded legumes as living mulches in sweet corn. Pages 171–175 *in* Proceedings of the 34th Northeastern Weed Science Society Meeting

Vrabel TE, Minotti PL, Sweet RD (1981) Legume sods as living mulches in sweet corn. Pages 158–159 *in* Proceedings of the 35th Northeastern Weed Science Society Meeting

Wilson HP, Waterfield RL (1968) Activity of herbicides in sweet corn. Pages 47–53 *in* Proceedings of the 22nd Northeastern Weed Science Society Meeting

Table 2.1. Living mulch herbicide treatments during 2014, 2015 and 2016. Reference plots are also listed.

No:	Treatment	First application		Second application	
		Herbicide	Rate (kg ai ha^{-1})	Herbicide	Rate (kg ai ha^{-1})
2014					
1.	Control (hand-weeded, weed-free)				
2.	Mowing (no herbicide treatments)				
3.	Metribuzin low rate	Metribuzin	0.08	Metribuzin	0.08
4.	Metribuzin high rate	Metribuzin	0.136	Metribuzin	0.136
5.	Rimsulfuron low rate	Rimsulfuron	0.0085	Rimsulfuron	0.0085
6.	Rimsulfuron high rate	Rimsulfuron	0.017	Rimsulfuron	0.017
7.	Halosulfuron	Halosulfuron	0.053	Halosulfuron	0.053
2015 and 2016					
1.	Control (hand-weeded, weed-free)				
2.	Untreated living mulch check (no herbicide treatments)				

3.	Weedy check (no living mulch, no herbicide treatments)				
4.	Metribuzin + halosulfuron	Metribuzin	0.1	Halosulfuron	0.05
5.	Metribuzin + rimsulfuron	Metribuzin	0.1	Rimsulfuron	0.007
6.	Rimsulfuron + metribuzin	Fomesafen	0.012	Metribuzin	0.15
7.	Fomesafen + metribuzin	Rimsulfuron	0.007	Metribuzin	0.15

Table 2.2. Tomato yield, and living mulch and weed parameters during the 2014 preliminary trial year.[a, b,]

Treatment	Tomato yield (tons ha^{-1})	Average living mulch cover (%) [c]	Average weed cover	Average living mulch height (cm) [c]	Living mulch biomass (tons ha^{-1}) [d]
Control	66 ab	-	-	-	-
Mowing	42 c	38 ab	41 a	29 b	1.5 a
Metribuzin low rate	67 ab	66 a	16 b	70 a	1 a
Metribuzin high rate	73 a	49 ab	9 b	47 ab	0.5 a
Rimsulfuron low rate	53 bc	64 ab	22 ab	58 ab	1.1 a
Rimsulfuron high rate	76 a	29 b	21 ab	31 b	0.5 a
Halosulfuron	52 bc	69 a	23 ab	73 a	1.4 a
Standard error	4	8	5	7	0.2

[a] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test ($\alpha = 0.05$).

[b] Visual estimations (percentages) were in absolute terms, so living mulch and weed cover may not add to 100%.

[c] Average of living mulch and weed cover estimated multiple times during the season

[d] Oven-dried (two weeks at 75C) dry matter

Table 2.3. Tomato yield, and living mulch and weed parameters during 2015.[a, b, c]

Treatment	Tomato yield	Average LM cover	Average weed cover	LM cover harv.	Weed cover harv.	Average LM height	LM height harv.	LM density	Weed density	LM biomass	Weed biomass
	(tons ha^{-1})	(%) [d]				(cm) [d]		(plants m^{-2})		(tons ha^{-1}) [e]	
Control	33 a	-	-	-	-	-	-	-	-	-	-
Untreated living mulch check	12 b	56 a	25 b	65 a	34 a	82 a	114 a	118 a	25 a	2.7 a	2.1 a
Weedy check	12 b	-	50 a	-	62 a	-	-	-	30 a	-	2.6 a
Metribuzin + halosulfuron	16 b	63 a	26 b	87 a	27 a	85 a	105 ab	114 a	19 a	2.8 a	1.3 a
Metribuzin + rimsulfuron	19 ab	60 a	20 b	62 a	27 a	77 a	85 bc	130 a	17 a	2.3 a	0.7 a
Fomesafen + metribuzin	21 ab	33 a	30 ab	35 a	50 a	64 a	74 c	94 a	20 a	2.4 a	0.9 a

Rimsulfuron + metribuzin	27 ab	53 a	28 ab	48 a	44 a	65 a	77 c	95 a	12 a	2.1 a	0.4 a
Standard error	5	9	9	13	12	8	6	22	5	0.6	1

[a] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test ($\alpha = 0.05$).

[b] Visual estimations (percentages) were in absolute terms, so living mulch and weed cover may not add to 100%.

[c] Abbreviations: LM, living mulch; harv., at beginning of tomato harvest.

[d] Average of living mulch and weed cover estimated multiple times during the season.

[e] Oven-dried (two weeks at 75C) dry matter.

Table 2.4. Tomato yield, and living mulch and weed parameters during 2016.[a, b, c]

Treatment	Tomato yield	Average LM cover	Average weed cover	LM cover harv.	Weed cover harv.	Average LM height	LM height harv.	LM density	Weed density	LM biomass	Weed biomass
	(tons ha^{-1})	(%) [d]				(cm) [d]		(plants m^{-2})		(tons ha^{-1}) [e]	
Control	101 a	-	-	-	-	-	-	-	-	-	-
Untreated living mulch check	29 d	82 a	25 c	87 a	19 b	77 a	116 a	132 a	84 ab	2.8 a	2.1 b
Weedy check	37 cd	-	98 a	-	98 a	-	-	-	141 a	-	9 a
Metribuzin + halosulfuron	59 bc	85 a	10 c	94 a	4 b	62 b	100 b	146 a	46 b	2.5 a	0.3 b
Metribuzin + rimsulfuron	66 b	76 a	11 c	85 a	9 b	54 b	81 c	143 a	26 b	1.4 b	0.4 b
Fomesafen + metribuzin	58 bc	21 c	55 b	40 b	35 b	42 c	67 c	121 a	43 b	0.7 b	2 b

Rimsulfuron + metribuzin	60 bc	42 b	49 b	78 a	29 b	40 c	75 c	133 a	55 b	1.3 b	1.4 b
Standard error	5	5	4	7	7	2	3	13	15	0.3	1

[a] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test (α = 0.05).

[b] Visual estimations (percentages) were in absolute terms, so living mulch and weed cover may not add to 100%.

[c] Abbreviations: LM, living mulch; harv., at beginning of tomato harvest.

[d] Average of living mulch and weed cover estimated multiple times during the season.

[e] Oven-dried (two weeks at 75C) dry matter.

Table 2.5. Nutrient concentrations in tomato leaf tissue during the 2015 and 2016 trial years.[a, b]

Treatment	N	P	K	Ca	Mg	S	Mn	Fe	Cu	B	Zn
	(%)						(ppm)				
2015											
Control	4.4 a	0.35 a	2.5 a	3.9 a	0.44 a	0.33 ab	314 a	277 a	84 a	9 a	37 a
Untreated living mulch check	4.2 a	0.32 a	2.8 ab	3.5 ab	0.42 a	0.3 b	262 ab	234 a	111 a	12 a	30 a
Weedy check	4.2 a	0.37 a	2.7 ab	3.5 ab	0.41 a	0.3 b	245 ab	219 a	141 a	12 a	29 a
Metribuzin + halosulfuron	4.3 a	0.34 a	3 ab	3.4 ab	0.41 a	0.3 b	254 ab	210 a	83 a	11 a	30 a
Metribuzin + rimsulfuron	4.4 a	0.37 a	3.1 a	3.3 ab	0.44 a	0.32 ab	264 ab	202 a	86 a	13 a	32 a
Fomesafen + metribuzin	4.6 a	0.35 a	3 ab	3 b	0.42 a	0.33 ab	243 b	225 a	55 a	11 a	30 a
Rimsulfuron + metribuzin	4.5 a	0.37 a	3.1 a	3.3 ab	0.44 a	0.36 a	291 ab	218 a	74 a	13 a	34 a
Standard error	0.2	0.02	0.24	0.2	0.02	0.02	16	27	24	1	2
2016											
Control	3.5 a	0.29 ab	3.1 ab	1.9 a	0.34 a	0.67 b	42 a	114 a	8.7 a	16 a	26 a

Untreated living mulch check	3.4 ab	0.32 a	3.8 a	1.8 a	0.4 a	0.83 a	58 a	110 a	9 a	17 a	25 a
Weedy check	2.7 b	0.28 ab	3.1 b	1.9 a	0.34 a	0.72 ab	43 a	104 a	7.3 a	17 a	17 a
Metribuzin + halosulfuron	3.5 a	0.27 ab	3.4 ab	1.8 a	0.35 a	0.73 ab	48 a	100 a	7.9 a	16 a	16 a
Metribuzin + rimsulfuron	3.3 ab	0.26 b	3 b	2 a	0.35 a	0.68 ab	44 a	103 a	6.8 a	15 a	16 a
Fomesafen + metribuzin	3.5 a	0.3 ab	3.4 ab	2 a	0.38 a	0.72 ab	53 a	122 a	7.9 a	16 a	22 a
Rimsulfuron + metribuzin	4.5 a	0.37 a	3.1 a	3.3 ab	0.44 a	0.36 a	291 ab	218 a	74 a	13 a	34 a
Standard error	0.2	0.01	0.14	0.1	0.01	0.03	5.2	6.8	0.5	0.9	5

[a] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test ($\alpha = 0.05$).

[b] Abbreviations: N, nitrogen; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; S, sulfur; Mn, Manganese; Fe, iron; Cu, copper; B, boron; Zn, zinc.

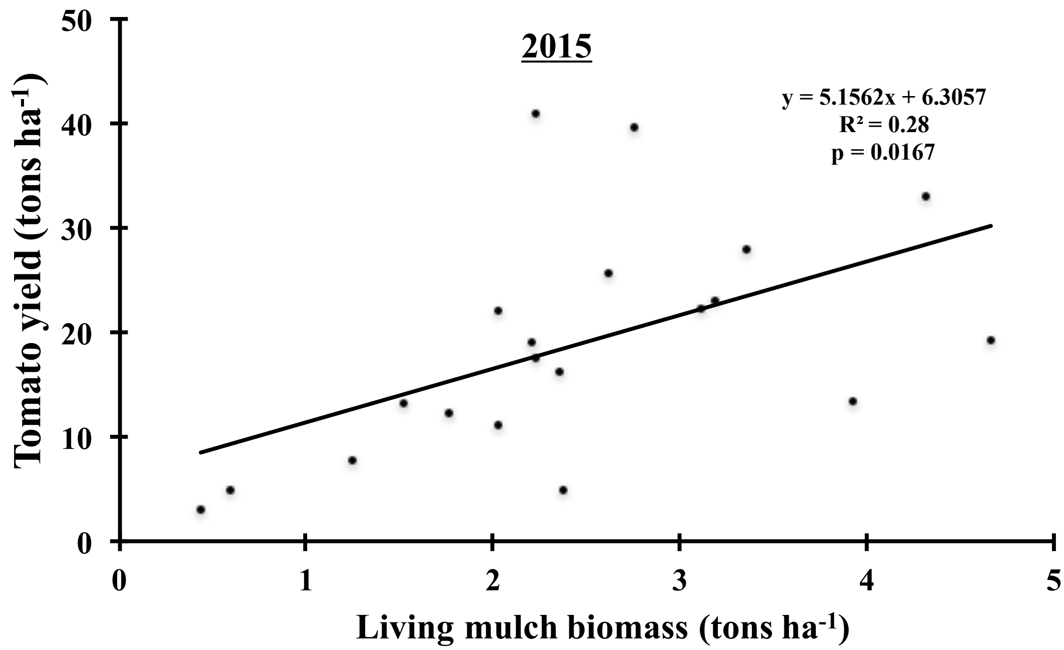

Figure 2.1. Relationship (linear regression, α = 0.05) between tomato yield and living mulch biomass (oven-dried, two weeks at 75 C) during 2015. Herbicides treatments and the untreated living mulch check (with no herbicide treatments) are represented here.

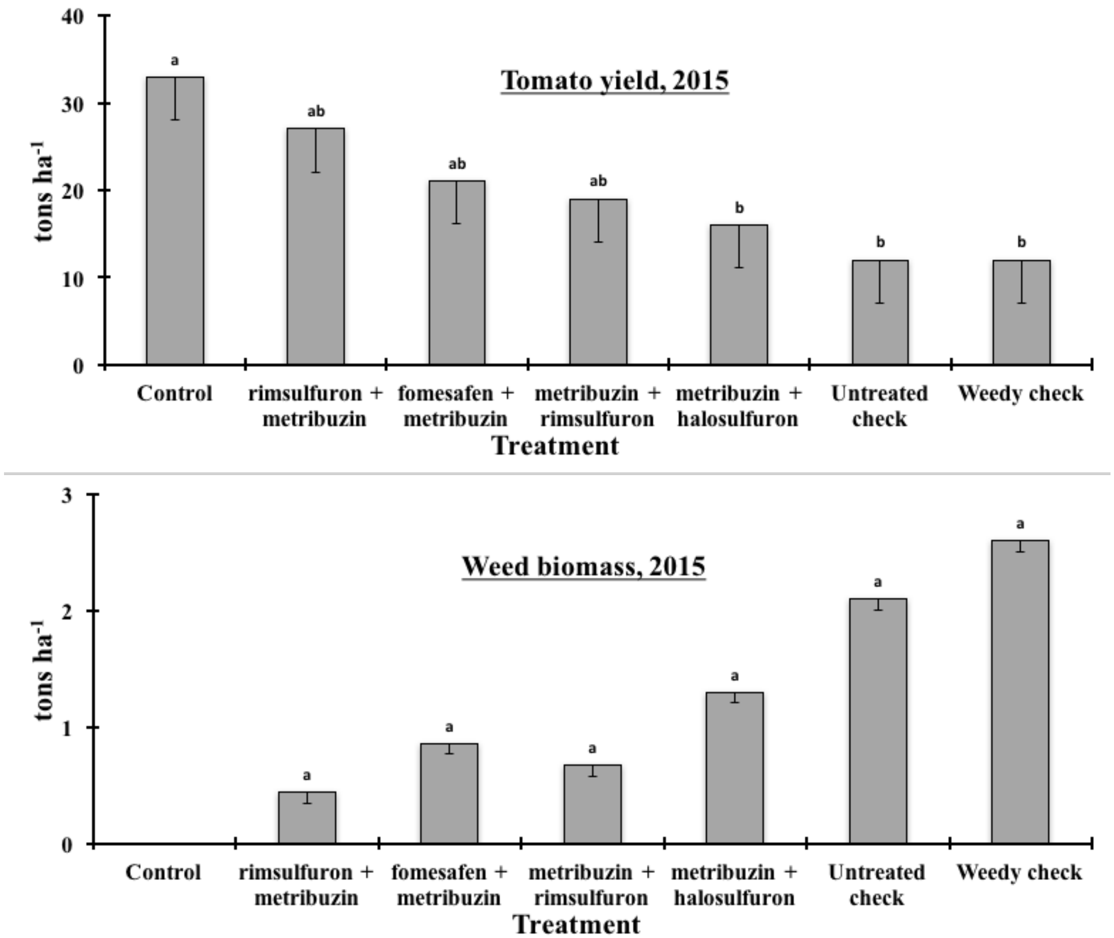

Figure 2.2. Tomato yield (± SE) (top) and weed biomass (± SE) (bottom) during 2015. Treatment comparisons were made using Tukey's test (α = 0.05); treatment bars not marked with the same letter(s) are significantly different.

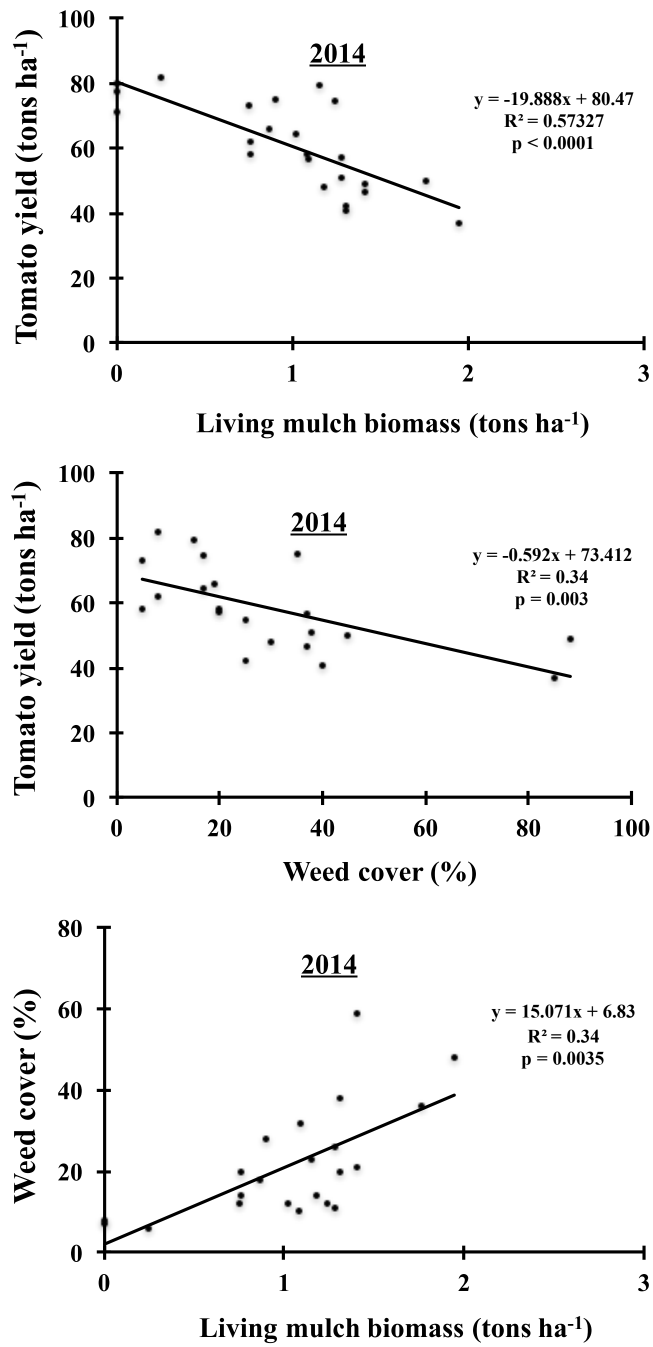

Figure 2.3. Relationships (linear regression, $\alpha = 0.05$) between tomato yield and living mulch biomass (oven-dried, two weeks at 75 C) (top), tomato yield and weed cover (center), and weed cover and living mulch biomass (bottom) during the 2014 preliminary trial year.

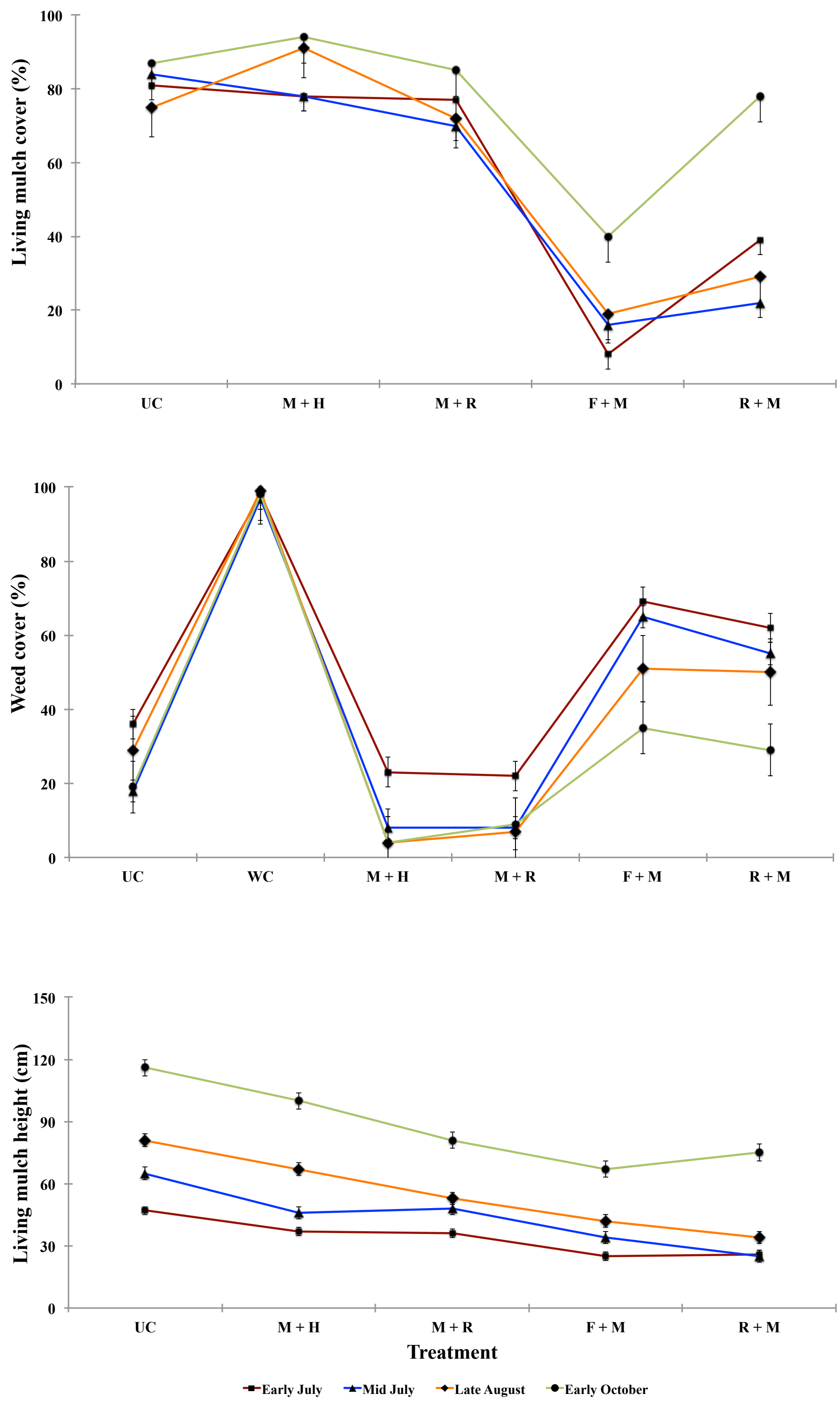

Figure 2.4. Living mulch cover (top), weed cover (center) and living mulch height (bottom) (± SE) at different times during 2016. Abbreviations for treatments: UC,

untreated living mulch check; WC, weedy check; F, fomesafen; H, halosulfuron; M, metribuzin; R, rimsulfuron; M + R-L, metribuzin 0.05 + rimsulfuron 0.005; M + R-H, metribuzin 0.1 + rimsulfuron 0.007.

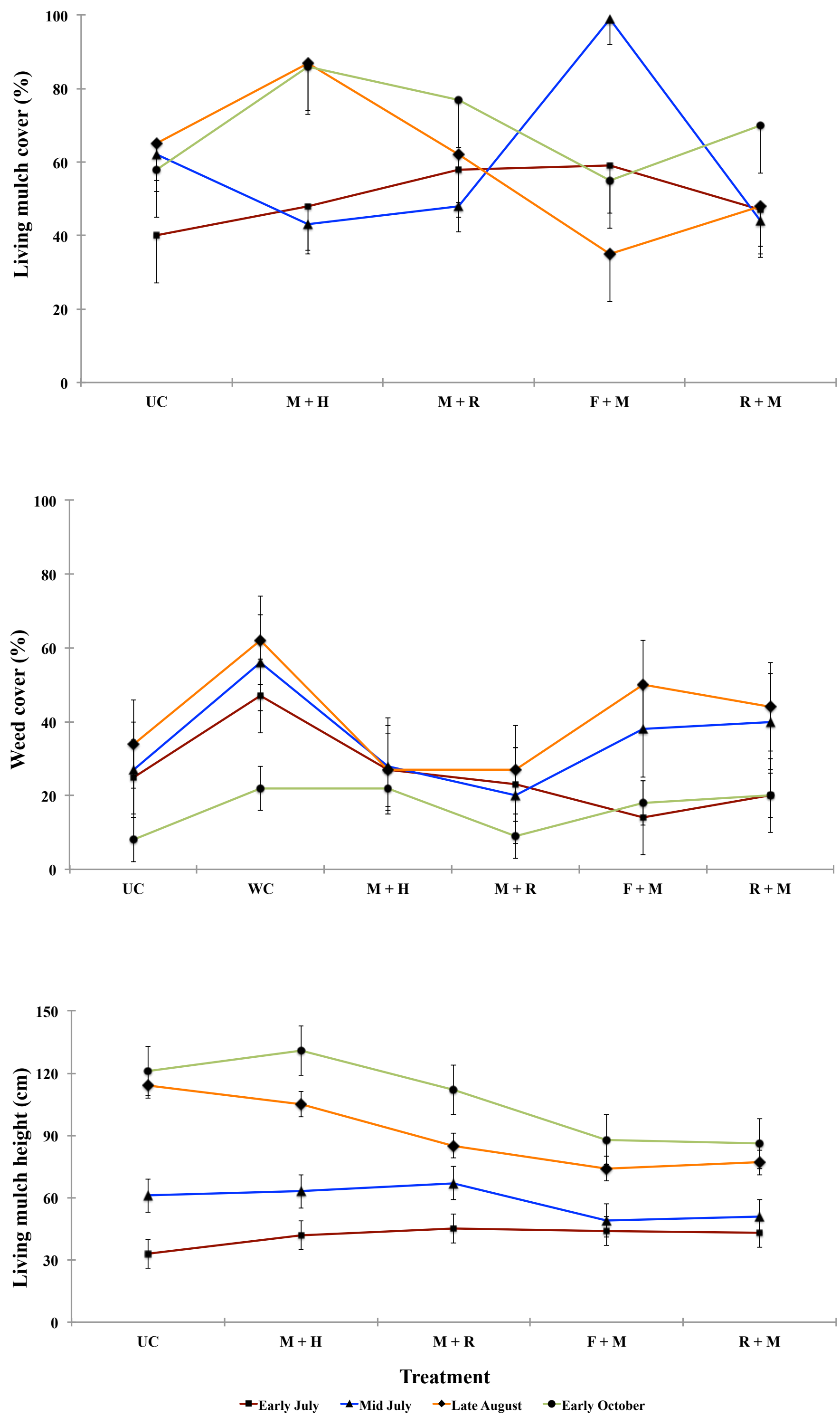

Figure 2.5. Living mulch cover (top), weed cover (center) and living mulch height (bottom) (± SE) at different times during 2015. Abbreviations for treatments: UC,

untreated living mulch check; WC, weedy check; F, fomesafen; H, halosulfuron; M, metribuzin; R, rimsulfuron; M + R-L, metribuzin 0.05 + rimsulfuron 0.005; M + R-H, metribuzin 0.1 + rimsulfuron 0.007.

CHAPTER THREE

Reduced-Rate Herbicide Combinations to Target Weeds in Living Mulch Systems

Introduction

As we attempt to make our farming systems more sustainable, cover crops have gained popularity. In modern agriculture, cover crops are typically planted after the harvest of the main crop. But, they can also be used as living mulches alongside cash crops, which may provide additional benefits. One of the chief goals of living mulch research has been to reduce soil erosion. In combination with no-till, living mulch research laid emphasis on cultivating major row crops in perennial living mulch sods.

Both annual and perennial living mulch systems are effective deterrents to inter-row tillage. Perennial living mulches may additionally eliminate primary tillage operations. From corn (*Zea mays* L.) planted into existing alfalfa (*Medicago sativa* L.) sod, Moomaw and Martin (1976) reported that initial plowing can be eliminated when herbicides are used to suppress the sod. Although reduction in tillage was achieved, herbicide input increased because crop yields were adversely affected when living mulches were not controlled (Hall et al. 1984; Moomaw and Martin 1976). So, herbicides were not only used for weed control, but also for suppressing the living mulch.

But, excessive herbicide injury to living mulches is a major challenge in chemical suppression of living mulches (Hartwig and Hoffman 1975). This need to control living mulches to prevent crop yield losses not only requires greater amounts of herbicides, but also reduces soil cover and biomass production by the living mulch (Linscott and Hagin 1975; Robertson et al. 1976). For example, in a bahiagrass (*Paspalum notatum* Flueggè) sod in no-till corn, additional nitrogen and herbicides were used to maintain corn yield, but this drastically reduced biomass production by the bahiagrass (Robertson et al. 1976).

When cultural management techniques like mowing are used instead of herbicides, living mulch recovery can be too quick, leading to undue competition with the cash crop (Hartwig 1976).

On the other hand, herbicides suppress weeds more effectively in the presence of a living mulch (Hartwig 1977). When living mulch injury from herbicide applications is not too severe, weed suppression can be acceptable, but greater living mulch injury provides the weeds with a competitive advantage (Echtenkamp and Moomaw 1989; Hughes and Sweet 1979). Living mulches, however, may not be able to suppress weeds adequately by themselves, without assistance from herbicide applications. Vrabel et al. (1980) reported that even vigorous (in terms of biomass production) living mulches can be ineffective at suppressing weeds. So, in herbicide management of living mulches, herbicide applications must augment the weed suppression provided by the living mulches without severely affecting living mulch vigor.

While living mulches can be competitive with cash crops, some studies have reported that living mulches can prevent their growth from adversely affecting crop yield. Vrabel et al. (1980) found that living mulches that generated the largest amount of biomass caused the least reduction in sweet corn yield. Other studies reported that living mulches could compete exclusively with weeds. In a broccoli (*Brassica oleracea* L. var. *botrytis* L.)-winter rye (*Secale cereale* L.) intercropping system, the living mulch effectively competed with weeds without reducing broccoli yield (Brainard and Bellinder 2004). Some studies even reported that legume living mulches improved crop growth and yield (Vrabel et al. 1981). Typically, effects of living mulch-crop competition on crop yield are absent during wet years, but apparent during dry soil conditions (Adams et al. 1970; Echtenkamp and Moomaw 1989).

Losses in crop yield due to living mulch-cash crop competition can be high when living mulches are planted too early relative to the cash crop (Brainard and Bellinder 2004; Vrabel et al. 1980). But, early-planted living mulches can suppress weeds more effectively (Brainard and Bellinder 2004). Earlier living mulch planting can also minimize or eliminate inter-row tillage. Brainard et al. (2004) reported that, in cabbage (*Brassica oleracea* var. *capitata* L.), multiple inter-row tillage operations were required for weed control when living mulches were planted a few weeks after cabbage was transplanted. Besides, late planted living mulches would generate lower biomass and leave soil bare for a considerable length of time, which are undesirable outcomes in a living mulch system.

Given the merits and demerits of early and late planting of living mulches, maximum benefit might be attained by planting the living mulch and the cash crop at approximately the same time. Vrabel et al. (1980) had reported this from an evaluation of different living mulch planting times in sweet corn. In case of perennial living mulches, crops must be planted into this sod. So, greater herbicide input may be essential for adequate living mulch suppression (Peters and Currey 1970), and this may increase each year as the sods establish better (Cardina and Hartwig 1980). When living mulches are planted along with the cash crop, lower herbicide rates might be sufficient because of their smaller size.

Lower herbicide rates may also be an effective strategy to prevent excessive living mulch injury. However, literature on appropriate herbicide rates is lacking. Earlier studies reported that lower herbicide rates did not suppress living mulches, while higher rates suppressed them too severely (Hughes and Sweet 1979). Living mulch management techniques must curb living mulch growth for some time, but must not severely affect their recovery. When overall herbicide input is reduced through reduction in application rates, different types of herbicides can be used in order to target a greater number of weed species.

Although herbicide combinations were used to suppress living mulches in several studies, they were sprayed in a single application (Cardina and Hartwig 1980; Hartwig 1976; Linscott and Hagin 1975; Hartwig 1977). Further research is required to assess the potential for using the differences in herbicide characteristics by spraying the different herbicides at different times. By spacing out herbicide applications, longer lasting weed control may also be achieved. Due to potential differences in herbicide effects on weeds and living mulches, the right herbicide combinations could provide living mulches with a competitive advantage over weeds. Herbicide applications consisting of only one herbicide, and overall lower herbicide quantities, might also prevent excessive loss in soil cover due to living mulch injury.

From an evaluation of living mulches in corn, Hoffman and Hartwig (1975) highlighted the importance of developing herbicide rates and timing that can enable living mulches to provide consistent soil cover. The potential of residual herbicides in reducing overall herbicide input and number of herbicide applications, through better weed control has also been reported (Moomaw and Martin 1976). In our trials, it was expected that herbicides which have predominantly pre-emergence activity, when applied on two-to-three week old cover crops, will not affect the cover crop too severely, and will have residual activity against future weed emergence.

To increase the post-emergence activity of (primarily pre-emergence) herbicides, surfactants can be used; and this strategy can reduce herbicide rates by five to ten times (Akobundu et al. 1975; Currey and Cole 1966; Dickerson and Sweet 1968; Liu et al. 1966; Wilson and Waterfield 1968). Since cover crops typically emerged sooner than weeds in our trials, such applications of primarily pre-emergent herbicides with a surfactant are likely to injure the smaller weeds more than the larger cover crop. In this way, by averting excessive living mulch injury, good soil cover can be maintained throughout the season.

Literature on herbicide management of living mulches in perennial no-till corn and soybean systems, is sufficient to establish the potential of living mulch systems. Further research is required with emphasis on herbicide reduction and herbicide application techniques. Living mulch-weed-herbicide interactions also need to be studied in detail beyond the realm of crop yield. The goal of this project was to generate more information in these areas. Through evaluation of several herbicide combinations, the main objective was to understand the potential for herbicide applications to injure weeds disproportionately more than the living mulch. No cash crop was planted in this experiment, but the cover crops were considered as living mulches for the sake of discussion.

Materials and Methods

Field trials were conducted in 2015 and 2016 at the Homer C. Thompson Vegetable Research Farm in Freeville, NY. The soils at this location are Howard gravel loam (Loamy-skeletal mixed mesic Glosoboric Hapludalf), with pH 6.0 to 6.6. Trials were set up at different fields each year. Sesbania [*Sesbania sesban* (L.) Merr.] and sunnhemp (*Crotalaria juncea* L.), the two cover crops used in this experiment, are both tropical/sub-tropical legumes.

Field preparation and planting: To prepare for planting, fields were moldboard plowed, disked and harrowed. Even though this experiment did not include a cash crop, fertilization was done like for a vegetable planting. This is because the goal of this experiment was to evaluate the treatments as if the cover crops were living mulches in vegetables. The experimental fields were fertilized with N, P and K, all applied at 100 kg ha^{-1} rate through 13-13-13 fertilizer. Sesbania and sunnhemp were seeded at 23 cm row spacing using a grain drill, during the last week of May. Due to unsuitable settings in the grain drill for sunnhemp seeds, sunnhemp was seeded at rates of 65 and 90 kg ha^{-1} in 2015 and 2016, respectively. Cover crops were planted in 1.8 m strips. In these strips, treatments were randomly assigned to 1.8 by 3.1 m plots. The experiment was set up as a randomized complete block design with three replicates. Sesbania was not used in 2016 because of its poor emergence and growth in 2015. Irrigation was not required in 2015 since it was a wet year. In 2016, irrigation was provided several times due to severe drought conditions.

Treatments and data collection: Ten different herbicide-combination treatments were tested using fomesafen, halosulfuron, imazethapyr, metribuzin, rimsulfuron and s-metolachlor (Table 3.1). All herbicide applications used in the experiments were made post-emergent, with respect to both the cover crops and weeds. All herbicide applications included a non-ionic surfactant at 0.25% spray volume. Blanket applications of sethoxydim and clethodim (not in combination) were made over the entire trial at recommended rates for grass weed control. These applications were not part of the treatments, and were used because the primarily broadleaf herbicides in the treatments were assumed to be inadequate for grass weed control. Sethoxydim or clethodim applications did not have any visible effects on the legume cover crops.

Based on cover crop sensitivity, the herbicides were classified into two types. At the chosen application rates, Type 1 (fomesafen, rimsulfuron and s-metolachlor) herbicides caused more severe cover crop injury than Type 2 (halosulfuron, imazethapyr and metribuzin) herbicides. Each herbicide treatment was comprised of one application each of two herbicides. To understand the effects of the 1) order of application of Type 1 and Type 2 herbicides, and 2) different combinations of the two herbicide types, the results are also presented by grouping the ten herbicide treatments into four herbicide-type combinations: Type 1 + Type 1, Type 1 + Type 2, Type 2 + Type 1 and Type 2 + Type 2. Two references were used for comparison of cover crop and weed parameters: 1) untreated cover crop check, with no herbicide applications (except grass herbicides); and 2) weedy check, with no cover crops, herbicide applications (except grass herbicides), or other forms of weed control.

Pressurized (200-240 kPa) carbon dioxide backpack sprayers were used for herbicide application, with approximately 320 L ha^{-1} output. The boom was comprised of four flat-fan nozzles, providing a combined swath of 1.8 m at an operating height of about 50 cm from the ground. Typically, the cover crops emerged earlier than the weeds, and were about 20 cm tall at the time of weed emergence. The first herbicide applications were made at this stage in late June. The second herbicide applications were made during the third week of July. Towards the end of September, temperatures were low enough to considerably curb growth of the warm season cover crops. So, cover crop flowering was negligible and there was no seed set.

Percent cover crop cover and weed cover, and cover crop height were estimated at four different times during the season. Biomass and density of cover crops and weeds were measured at the beginning of September, aimed to coincide with the typical start of vegetable harvests in the region. Cover crop biomass and density were determined from two randomly selected 50 cm long stretch of living mulch row, at least 60 cm away from the plot edges. These values were subsequently converted into ha^{-1} unit. For weed biomass and density, 0.25 m^{-2} quadrats (50 by 50 cm) were used to sample two randomly chosen areas, again at a distance of at least 60 cm away from the plot edges. Both cover crops and weeds were cut at ground level for estimation of aboveground biomass. Grass and broadleaf weeds were both collected during sampling. Fresh weight was measured immediately after sampling, and dry matter weight was measured after oven-drying for two weeks at 75 C.

Data analyses: Living mulch (cover, height, density and biomass) and weed (cover, density and biomass) parameters were subjected to analysis of variance (ANOVA) and regression analyses at 5% level of significance. To compare treatment differences, Tukey's HSD test was used. Herbicide treatments were considered as fixed effects. Due to drastically different climatic conditions in 2015 and 2016, data across years were not combined for analyses, unless where mentioned. Statistical analyses were carried out using JMP Pro 12 (2013 SAS Institute Inc., Cary, NC) software.

Results and Discussion

Above average rainfall was received in 2015, whereas the summer of 2016 had a prolonged drought period with an overall below average rainfall. In 2015, emergence and growth of sesbania was unacceptable, and so, sesbania was not planted in 2016. Small seed size of sesbania could be an issue for its emergence in cold or wet conditions. No data was collected from sesbania plots in 2015 because cover crop establishment was too poor to provide valid measurements. Therefore, the results presented here are only from sunnhemp. Major weeds in the experimental plots were Powell amaranth (*Amaranthus powellii* S. Watson), shepherd's purse [*Capsella bursa-pastoris* (L.) Medic.] lambsquarters (*Chenopodium album* L.), hairy galinsoga (*Galinsoga quadriradiata* Cav.) and common purslane (*Portulaca oleracea* L.). Greater treatment differences were observed in 2016, probably since much of the effects of competition between the cover crops and weeds which were exposed by the severe dry conditions during this year, was suppressed by the high amounts of rainfall received during 2015. Since maximum weed emergence happened in June, another reason could be the late planting of cover crops in 2015, which would have reduced the overall weed pressure.

When cover crop and weed data from both years were pooled together, average cover crop biomass during 2015 was not significantly different from 2016 ($p = 0.21$). Even though irrigation was provided in 2016, the two years received very different amounts of precipitation. In case of all living mulch treatments, except fomesafen + metribuzin ($p = 0.004$), there were no significant treatment by year interactions regarding cover crop biomass. So, given irrigation, the cover crop demonstrated capacity for uniform growth and vigor during both the wet (2015) and dry (2016) summer. Regarding the degree of cover crop control, this could mean that the herbicide treatments had adequate predictability between seasons with different climatic conditions.

Weed biomass in the weedy check was significantly higher in 2016 (4.2 tons ha^{-1}) than in 2015 (2.18 tons ha^{-1}) ($p = 0.0009$) (Table 3.2; Table 3.3). However, there was no overall treatment by year interaction ($p = 0.13$). This suggests that the cover crop-herbicide treatment combinations had predictability in their degree of weed control, regardless of the absolute weed pressure during the season.

Year 1 (2015). Cover crop biomass from all the herbicide treatments (3.8 to 7 tons ha^{-1}) were similar (Table 3.2). And, but for metribuzin + fomesafen (3.8 tons ha^{-1}) ($p = 0.027$), all the herbicide treatments were similar to the untreated check (7 tons ha^{-1}). Therefore, the herbicide treatments did not cause significant losses in cover crop biomass. Reduction in cover crop biomass, compared with the untreated check, was 17 (imazethapyr + rimsulfuron, 5.8 tons ha^{-1}) to 46% (metribuzin + fomesafen, 3.8 tons ha^{-1}).

Density of cover crop stand is also crucial to the functions of a living mulch system. It is desirable that herbicide applications do not cause cover crop mortality, since gaps in the cover crop stand can cause an outbreak of weeds (Echtenkamp and Moomaw 1989; Hughes and Sweet 1979). Cover crop density was not affected by the herbicide applications, and all herbicide treatments were similar to each other and to the untreated cover crop check ($p = 0.9$) (Table 3.2). Herbicide-type combination also did not have any impact on cover crop stand density ($p = 0.86$) (Table 3.4).

All herbicide-type combinations (0.06 to 0.44 tons ha^{-1}), and the untreated cover crop check (0.18 tons ha^{-1}) had similar weed biomass, and they were all lower than the weedy check (2.18 tons ha^{-1}) ($p < 0.0001$) (Table 3.4). Since weed biomass in the untreated check was numerically lower than in some herbicide treatments, herbicides did not necessarily improve weed control. Herbicide-type combinations that injured cover crops to a lesser degree (Type 2 + Type 2 (0.06 tons ha^{-1}) and Type 2 + Type 1 (0.14 tons ha^{-1})) had lower weed biomass than the herbicide-type combinations that injured the cover crops more severely (Type 1 + Type 2 (0.27 tons ha^{-1}) and Type 1 + Type 1 (0.44 tons ha^{-1})). Similar results have been reported by several researchers, where excessive cover crop injury from herbicides have led to increased weed pressure (Echtenkamp and Moomaw 1989; Hughes and Sweet 1979).

Weed density was not significantly affected by the cover crop treatments (11 to 28 plants m^{-2}) (Table 3.2) ($p = 0.5$), or herbicide-type combinations (11 to 22 plants m^{-2}) (Table 3.4) ($p = 0.19$). These were even similar to the weedy check (27 plants m^{-2}). So, the cover crops and the herbicide applications most likely stunted weed growth through competitive and chemical stress rather than kill the weeds. This is supported by the weed biomass data. Weed density or weed biomass were not affected by herbicide application or type (Table 3.2; Table 3.4). But compared to the weedy check, treatments were effective in suppressing weeds. In seven of the 11 cover crop treatments, weed biomass was more than an order of magnitude lower than the weedy check (Table 3.2).

Average weed cover in all cover crop treatments (2 to 5%), including the untreated check (4%), were similar to each other, and all were lower than the weedy check (46%) ($p < 0.0001$) (Table 3.2). The final weed cover at the end of the season in

October, showed a greater disparity between the weedy check (92%) and the living mulch treatments (1% to 16%) ($p < 0.0001$) (Figure 3.1). The untreated cover crop check had 8% weed cover at the end of the season, demonstrating the potential of a simple cover crop cover in reducing weed cover by up to 84% in the inter-row space.

The order of application of Type 1 and Type 2 herbicides did not have any significant impact regarding any weed parameter in 2015. As mentioned before, the above average rainfall during this year could have nullified much of the competitive and chemical effects of the cover crop-herbicide treatments on weeds. Additionally, since maximum weed emergence occurs in June, late planting of cover crops in 2015 could have suppressed the effects of the herbicide-type combinations. In an earlier living mulch experiment in broccoli at the same farm where our field trials were conducted, when rye was inter-seeded a few weeks after broccoli transplanting, it did not have any pronounced effect on weed control because the later weed emergence was weak (Brainard and Bellinder 2004). During 2015, relative to the trial presented in this discussion (average of 0.4 tons ha^{-1}), weed biomass was higher in a living mulch trial (average of 1.3 tons ha^{-1}) in the same field (4.6 m away) where living mulches were planted a month earlier. This is further indication that late planting of cover crops in 2015 could have made the effects of the different herbicide-type combinations on weeds less pronounced.

Year 2 (2016). In several herbicide treatments, cover crop cover and biomass were numerically higher than in the untreated check (Table 3.3). Cover crop biomass from metribuzin 0.1 + rimsulfuron 0.007, metribuzin 0.05 + rimsulfuron 0.005 and metribuzin + halosulfuron were 5.6 tons ha^{-1}, 5.6 tons ha^{-1} and 6.1 tons ha^{-1}, respectively, compared with 5.5 tons ha^{-1} from the untreated check. Although not statistically significant, this could suggest that some of the herbicide treatments not only averted severe cover crop injury, but they were additionally successful in affecting weeds disproportionately more than the cover crops, thereby providing a less competitive environment for the cover crop relative to the untreated check.

This is corroborated by the negative correlation of weed biomass with both cover crop biomass ($p = 0.002$) and cover in late August ($p = 0.007$). Instead of interpreting these relationships solely as increased weed suppression by more vigorous cover crop stands, it can also be considered as an enhancement in cover crop growth when weed injury/suppression by the herbicide treatments have been substantial without excessive cover crop injury. In chemical management of living mulches, one of the main constraints is that, the herbicides/application rates required to obtain maximum crop yield damages the living mulches too severely (Hartwig and Hoffman 1975), which would affect their sustainability functions. In the context of a living mulch system, in the combination of living mulch and weeds in the inter-row space, the ability of herbicide treatments to asymmetrically affect weeds could make it possible to obtain satisfactory crop yields without compromising on living mulch vigor.

While majority of the cover crop treatments were similar to each other in terms of cover crop biomass, herbicide treatments beginning with metribuzin (5.6, 5.6 and 6.1 tons ha^{-1}) and imazethapyr (5.2 and 5.2 tons ha^{-1}) recorded the highest cover crop biomass, along with the untreated cover crop check (5.5 tons ha^{-1}) (Table 3.3). In case of cover crop density, only Type 1 + Type 2 (103 plants m^{-2}) was lower than the untreated check (174 plants m^{-2}) ($p = 0.038$) (Table 3.5). Along with the results from 2015, this confirms that the herbicide treatments did not cause any gaps in the cover crop stand. Soil cover from the cover crops was also considerable in three of the four herbicide-type combinations (Table 3.5), indicating that herbicide applications were effective in preventing considerable, long-term loss in soil cover.

Throughout the growing season, however, in mid-July (18%; $p < 0.0001$), late July (13%; $p < 0.0001$) and early August (15%; $p < 0.0001$), Type 1 + Type 2 had lower cover crop cover than all other herbicide-type combinations and the untreated check (Figure 3.2). By late August, cover crops in Type 1 + Type 2 regrew only enough to provide 52% ground cover, which was still lower than cover crop cover in the other herbicide combinations (93 to 98%) ($p = 0.0004$) (Table 3.5). In case of cover crop height also, throughout the season, cover crop height between Type 1 + Type 1, Type 2 + Type 1 and Type 2 + Type 2 were similar to each other and to the untreated check, but cover crops in Type 1 + Type 2 were shorter ($p = 0.0005$ in mid-July; $p < 0.0001$ in late July; $p < 0.0001$ in early August and $p < 0.0001$ in late August) (Figure 3.2).

Cover crops in Type 1 + Type 2 were most likely affected by higher weed pressure. This could have affected the cover crops more adversely than even the herbicide applications. While in late August, weed cover in Type 1 + Type 2 (55%) was lower than the weedy check (98%) ($p = 0.014$) (Table 3.5), in early August, they were similar (74 and 92%, respectively) ($p = 0.59$) (Figure 3.2). These results are consistent with many other reports of increased weed pressure following severe herbicide damage to cover crops (Echtenkamp and Moomaw 1989; Hartwig 1977; Hughes and Sweet 1979). At the time of the first herbicide application, the cover crop is young. So, when a Type 1 herbicide is applied first, cover crop injury is severe enough to affect recovery.

For example, cover crop biomass in fomesafen + metribuzin, with a first application of fomesafen, a Type 1 herbicide, was only 1.7 tons ha^{-1} (Table 3.3). This was significantly lower than cover crop biomass in most of the other treatments, especially in those with a first application of Type 2 herbicide ($p = 0.0002$). Among the herbicides, most severe cover crop injury was caused by fomesafen. Consequently, due to decreased competition from the cover crop, there will likely be an elevation in weed growth. Weed emergence following the herbicide application will also be relatively unchecked if this first herbicide application cannot provide any residual soil activity against weeds. This increased weed pressure can further affect cover crop growth. Even though, in 2016, weed cover decreased with increasing cover crop biomass ($p < 0.0001$), there was no relationship between weed density and cover crop biomass ($p = 0.6$). These corroborate earlier indications that the combination of cover crops and herbicides hampered weed growth rather than kill the weeds. Perhaps, in case of Type 1 + Type 2 treatments, herbicide applications may have reduced weed density, probably triggering weeds to grow into larger individual plants relative to weeds in other plots, leading to production of considerable weed biomass.

Interestingly, two applications of Type 1 herbicides (Type 1 + Type 1), which the cover crops are more sensitive to, led to taller cover crop plants than Type 1 + Type 2. So, after the first application of a Type 1 herbicide, if weed cover in Type 1 + Type 1 and Type 1 + Type 2 had been 1) higher than weed cover in the herbicide-type combinations with a first application of a Type 2 herbicide, and 2) comparable before the second herbicide application, then, the increased weed pressure resulting from the first application of a Type 1 herbicide could have been suppressed only by another Type 1 herbicide with greater post-emergent activity, and not by a Type 2 herbicide. The potentially more effective post-emergent weed suppression provided by a Type 1 herbicide at this stage could then explain the better cover crop growth in Type 1 + Type 1, compared with Type 1 + Type 2. However, at that time, average weed cover from only the Type 1 + Type 2 (40%) plots were higher than weed cover from Type 2 + Type 1 (6%; $p = 0.0001$) and Type 2 + Type 2 plots (6%; $p = 0.01$) (herbicide-type combinations with first application of a Type 2 herbicide). Moreover, average weed cover in the Type 1 + Type 1 (20%) plots was only half that in the Type 1 + Type 2 plots. As such, it is not clear why Type 1 + Type 2 plots had higher weed pressure, but that was the likely cause for decreased cover crop growth.

Cover crops in Type 1 + Type 2 (24 cm) were also shorter than in other herbicide-type combinations (34 to 37 cm), even early in the 2016 season, before the second herbicide applications ($p = 0.0005$) (Figure 3.2). Reductions in cover crop height are positive outcomes, and are expected from herbicide applications since cover crop height has considerable influence on crop yield. Tall living mulches can easily be too competitive with the cash crop by shading both the side and top portions of the crop canopy. In an earlier experiment, crop yields were reduced by 15% in the presence of a shorter living mulch of chewings fescue, whereas, crop yields were reduced by 46% by a taller rye plus oats plus vetch living mulch (Echtenkamp and Moomaw 1989).

But, living mulch stands that are too short might suppress weeds poorly. By late August 2016, the cover crops in fomesafen + metribuzin and rimsulfuron + metribuzin grew to 68 and 84 cm respectively, but were still shorter than cover crops in all other treatments ($p < 0.0001$) (Table 3.3). Corresponding weed biomass from these treatments were 1.1 and 1.6 tons ha^{-1}, respectively, which was numerically higher than in most of the treatments (0.3 to 1.6 tons ha^{-1}), and even the untreated check (1.1 tons ha^{-1}). So, if these reductions in height are associated with, or will be accompanied by, losses in cover crop cover or biomass, or increase in weed pressure, it is a critical loss in the objectives of establishing a living mulch system. In the aforementioned Echtenkamp and Moomaw (1989) study, even though crop yield was affected differently by the two living mulches, the living mulches produced similar amounts of biomass. The researchers attributed this outcome to their contrasting height and growth habit. Therefore, reductions in cover crop height, ground cover or biomass, leading to increased weed pressure are unwarranted because cash crops are more likely to be affected by weeds than by living mulches due to differences in planting design and plant geometry.

The untreated cover crop check, even without herbicide applications, suppressed weeds considerably during both 2015 and 2016, sometimes even better than some herbicide treatments (Table 3.2; Table 3.3). During late August, weed cover in Type 1 + Type 1 (27%) was approximately the same as weed cover in the untreated check (31%); but, weed cover in Type 1 + Type 2 was 55% (Table 3.5). In such situations, herbicide applications in living mulch systems become pointless, unless it can perform some other functions (like reduction in living mulch height) which can supersede the adverse effects of weed pressure on crop yield.

This capacity of cover crops for weed suppression in the absence of herbicides, along with the effects of herbicides on cover crop and weeds in Type 1 + Type 2, could explain the excellent weed suppression in Type 2 + Type 1. In 2016, weed biomass was lowest in Type 2 + Type 1 (0.6 tons ha^{-1}), and this was significantly lower than weed biomass from Type 1 + Type 1 ($p = 0.0009$) or Type 1 + Type 2 ($p = 0.012$) (Table 3.5). Type 2 + Type 1 (19%) and Type 2 + Type 2 (8%) also had the lowest weed cover in late August. During the first herbicide application, cover crops were usually larger than the weeds because cover crops emerged sooner, and were approximately 20 cm tall when weeds began to emerge. So, when a Type 2 herbicide is applied at this time, it does not affect the cover crop appreciably, but affects the smaller weeds much more. Due to this injury to weeds, and due to the residual activity provided by primarily pre-emergent herbicides like metribuzin, the cover crop stand also potentially gets a period of low competition (from weeds). This can be immensely beneficial for cover crop establishment, because the cover crop can then withstand a Type 1 herbicide. At the time of the second application of a Type 1 herbicide, weeds will likely still be smaller than the cover crop due to residual herbicide activity from the Type 2 herbicide. So, the second application would also target the weeds disproportionately.

Surfactants can improve the post-emergence activity of herbicides like atrazine; so their applications rates could potentially be reduced without substantial loss in efficacy (Akobundu et al. 1975; Currey and Cole 1966; Dickerson and Sweet 1968; Liu et al. 1966; Wilson and Waterfield 1968). All herbicides in our experiment, including metribuzin, were used with a non-ionic surfactant. So, a Type 2 herbicide like metribuzin, besides imparting its residual activity to the herbicide plan, also provided some degree of cover crop suppression. What the Type 2 + Type 1 herbicide treatments successfully achieved was the maintenance of healthy cover crop stands. This is further indication that, while the herbicide applications played an important role in weed control, the constant suppression of weeds by healthy cover crop stands was significant.

The herbicide treatment combinations demonstrated the capacity for targeting weeds asymmetrically, in a mix of cover crops and weeds. But, it would be of value to develop methods to further reduce cover crop height, and to achieve this without significant losses in soil cover and cover crop biomass, or increase in weed pressure. Overall, the herbicide applications were successful in averting considerable losses in cover crop cover, density and biomass. Many herbicides in the treatments were also used at rates that are much lower than their typical rates. Therefore, since the combination of cover crops and herbicides were effective in controlling weeds, these findings also indicate that reduction in herbicide input through reduction in herbicide application rates is possible in living mulch systems.

Acknowledgements

We thank Peter Putriment, Rebecca Wilk, Steve McKay, Rick Randolph and Ethan Tilebein for their assistance in management of the experiment. This project was partly supported by a grant from the Northeastern Sustainable Agriculture Research and Education (NE-SARE).

Literature cited

Adams WE, Pallas JE, Dawson RN (1970) Tillage methods for corn-sod systems in the Southern Piedmont. Agron J 62:646–649

Akobundu IO, Sweet RD, Duke WB, Minotti PL (1975) Weed response to atrazine and alachlor combinations at low rates. Weed Sci 23:67–70

Brainard DC, Bellinder RR (2004) Weed suppression in a broccoli–winter rye intercropping system. Weed Sci 52:281–290

Brainard DC, Bellinder RR, Miller AJ (2004) Cultivation and interseeding for weed control in transplanted cabbage. Weed Technol 18:704–710

Cardina J, Hartwig NL (1980) Suppression of crownvetch for no-tillage corn. Pages 53–58 *in* Proceedings of the 34th Northeastern Weed Science Society Meeting

Currey WL, Cole RH (1966) Comparisons of atrazine, atrazine-surfactant and atrazine-oil mixtures. Pages 297–300 *in* Proceedings of the 20th Northeastern Weed Science Society Meeting

Dickerson CTJ, Sweet RD (1968) Atrazine, oil, and 2,4-D for postemergence weed control. Pages 64–75 *in* Proceedings of the 22nd Northeastern Weed Science Society Meeting

Echtenkamp GW, Moomaw RS (1989) No-till corn production in a living mulch system. Weed Technol 3:261–266

Hall K, Hartwig NL, Hoffman LD (1984) Cyanazine losses in runoff from no-tillage corn in “living” and dead mulches vs. unmulched, conventional tillage. J Environ Qual 13:105–110

Hartwig NL (1976) Legume suppression for double cropped no-tillage corn in crownvetch and birdsfoot trefoil removed for haylage. Pages 82–85 *in* Proceedings of the 30th Northeastern Weed Science Society Meeting

Hartwig NL (1977) Nutsedge control in no-tillage corn with and without a crownvetch cover crop. Pages 20–23 *in* Proceedings of the 31st Northeastern Weed Science Society Meeting

Hartwig NL, Hoffman LD (1975) Suppression of perennial legume and grass cover crops for no-tillage corn. Pages 82–88 *in* Proceedings of the 29th Northeastern Weed Science Society Meeting

Hoffman LD, Hartwig NL (1975) Perennial soil conserving cover crops for no-till corn. Page 89 *in* Proceedings of the 29th Northeastern Weed Science Society Meeting

Hughes BJ, Sweet RD (1979) Living mulch: A preliminary report on grassy cover crops interplanted with vegetables. Page 109 *in* Proceedings of the 33rd Northeastern Weed Science Society Meeting

Linscott DL, Hagin RD (1975) Potential for no-tillage corn in crownvetch sods. Page 81 *in* Proceedings of the 29th Northeastern Weed Science Society Meeting

Liu LC, Ilnicki RD, Regan JB, Visinski EJ (1966) Naphthenic and paraffinic oils as adjuvants in atrazine and linuron sprays for weed control in corn. Pages 309–316 *in* Proceedings of the 20th Northeastern Weed Science Society Meeting

Moomaw RS, Martin AR (1976) Herbicides for no-tillage corn in alfalfa sod. Weed Sci 24:449–453

Peters RA, Currey WL (1970) Influence of sod species in no-tillage corn production. Pages 421–425 *in* Proceedings of the 24th Northeastern Weed Science Society

Meeting

Robertson WK, Lundy HW, Prine GM, Currey WL (1976) Planting corn in sod and small grain residues with minimum tillage. Agron J 68:271–274

Vrabel TE, Minotti PL, Sweet RD (1980) Seeded legumes as living mulches in sweet corn. Pages 171–175 *in* Proceedings of the 34th Northeastern Weed Science Society Meeting

Vrabel TE, Minotti PL, Sweet RD (1981) Legume sods as living mulches in sweet corn. Pages 158–159 *in* Proceedings of the 35th Northeastern Weed Science Society Meeting

Wilson HP, Waterfield RL (1968) Activity of herbicides in sweet corn. Pages 47–53 *in* Proceedings of the 22nd Northeastern Weed Science Society Meeting

Table 3.1. Cover crop herbicide treatments during 2015 and 2016. Reference plots are also listed.

No:	Treatment	First application		Second application	
		Herbicide	Rate (kg ai ha^{-1})	Herbicide	Rate (kg ai ha^{-1})
1.	Untreated cover crop check (no herbicide treatments)				
2.	Weedy check (no living mulches, no herbicide treatments)				
3.	Metribuzin + rimsulfuron low	Metribuzin	0.05	Rimsulfuron	0.005
4.	Metribuzin + halosulfuron	Metribuzin	0.05	Halosulfuron	0.05
5.	Metribuzin + fomesafen	Metribuzin	0.1	Fomesafen	0.012
6.	Metribuzin + rimsulfuron high	Metribuzin	0.1	Rimsulfuron	0.007
7.	Imazethapyr + rimsulfuron	Imazethapyr	0.04	Rimsulfuron	0.007
8.	Imazethapyr + fomesafen	Imazethapyr	0.04	Fomesafen	0.012
9.	s-metolachlor + rimsulfuron	s-metolachlor	0.35	Rimsulfuron	0.007
10.	s-metolachlor + fomesafen	s-metolachlor	0.35	Fomesafen	0.016
11.	Rimsulfuron + metribuzin	Rimsulfuron	0.007	Metribuzin	0.15
12.	Fomesafen + metribuzin	Fomesafen	0.012	Metribuzin	0.15

Table 3.2. Cover crop and weed parameters during 2015.[a, b, c]

Treatment	Average CC cover	Average weed cover	CC cover harv.	Weed cover harv.	Average CC height	CC height harv.	CC density	Weed density	CC biomass	Weed biomass
	(%) [d]				(cm) [d]		(plants m^{-2})		(tons ha^{-1}) [e]	
Untreated living mulch check	88 a	6 b	93 a	4 b	104 a	95 a	87 a	20 a	7 a	0.18 b
Weedy check	-	47 a	-	46 a	-	-	-	27 a	-	2.18 a
Metribuzin + rimsulfuron low	81 ab	5 b	84 a	3 b	82 ab	80 a	85 a	19 a	4.3 ab	0.14 b
Metribuzin + halosulfuron	88 a	3 b	93 a	2 b	86 ab	85 a	100 a	11 a	5 ab	0.06 b
Metribuzin + fomesafen	68 ab	4 b	83 a	3 b	81 ab	85 a	97 a	13 a	3.8 b	0.11 b
Metribuzin + rimsulfuron high	82 ab	4 b	82 a	3 b	79 b	79 a	100 a	18 a	4.3 ab	0.15b
Imazethapyr +	83 ab	5 b	87 a	3 b	83 ab	86 a	102 a	13 a	5.8 ab	0.19 b

rimsulfuron										
Imazethapyr + fomesafen	76 ab	3 b	91 a	2 b	78 b	80 a	112 a	16 a	4.7 ab	0.13 b
s-metolachlor + rimsulfuron	79 ab	8 b	94 a	5 b	88 ab	86 a	87 a	17 a	5.3 ab	0.43 b
s-metolachlor + fomesafen	65 ab	8 b	92 a	5 b	80 b	87 a	100 a	28 a	4.4 ab	0.45 b
Rimsulfuron + metribuzin	86 a	4 b	86 a	3 b	79 b	76 a	98 a	17 a	4.6 ab	0.32 b
Fomesafen + metribuzin	54 b	5 b	21 a	3 b	82 ab	86 a	95 a	16 a	4.7 ab	0.23 b
Standard error	6	0.9	2.4	0.9	5.1	5.4	11.3	5.2	0.6	0.3

[a] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test (α = 0.05).

[b] Visual estimations (percentages) were in absolute terms, so living mulch and weed cover may not add to 100%.

[c] Abbreviations: CC, cover crop; harv., during late August, typical vegetable harvest time in the region.

[d] Average of living mulch and weed cover estimated multiple times during the season.

[e] Oven-dried (two weeks at 75C) dry matter.

Table 3.3. Cover crop and weed parameters during 2016.[a, b, c]

Treatment	Average CC cover	Average weed cover	CC cover harv.	Weed cover harv.	Average CC height	CC height harv.	CC density	Weed density	CC biomass	Weed biomass
	(%) [d]				(cm) [d]		(plants m^{-2})		(tons ha^{-1}) [e]	
Untreated living mulch check	88 a	22 bcd	95 a	31 b	64 ab	106 a	174 a	103 a	5.5 a	1.1 bc
Weedy check	-	57 a	-	98 a	-	-	-	160 a	-	4.2 a
Metribuzin + rimsulfuron low	94 a	14 bcd	99 a	21 b	65 a	107 a	138 a	89 a	5.6 a	0.8 bc
Metribuzin + halosulfuron	90 a	8 cd	97 a	8 b	65 a	114 a	141 a	81 a	6.1 a	1 bc
Metribuzin + fomesafen	85 a	9 cd	99 a	13 b	55 ab	100 ab	148 a	57 a	3.8 ab	0.7 bc
Metribuzin + rimsulfuron high	87 a	4 d	98 a	6 b	52 bc	96 ab	131 a	57 a	5.6 a	0.3 c
Imazethapyr +	92 a	15 bcd	99 a	21 b	65 a	108 a	131 a	116 a	5.2 a	0.7 bc

rimsulfuron										
Imazethapyr + fomesafen	85 a	21 bcd	97 a	31 b	63 ab	103 ab	112 a	103 a	5.2 a	0.6 bc
s-metolachlor + rimsulfuron	86 a	25 bc	92 a	24 b	64 ab	100 ab	146 a	129 a	3.9 ab	1.5 bc
s-metolachlor + fomesafen	88 a	31 b	94 a	30 b	67 a	107 a	130 a	118 a	3.9 ab	1.6 b
Rimsulfuron + metribuzin	38 b	56 a	89 a	28 b	42 cd	84 bc	107 a	69 a	3.7 ab	1.1 bc
Fomesafen + metribuzin	10 c	62 a	15 b	82 a	36 d	68 c	100 a	53 a	1.7 b	1.6 b
Standard error	2.5	4.5	2.6	6.4	2.9	4.1	21	24.4	0.5	0.2

[a] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test ($\alpha = 0.05$).

[b] Visual estimations (percentages) were in absolute terms, so living mulch and weed cover may not add to 100%.

[c] Abbreviations: CC, cover crop; harv., during late August, typical vegetable harvest time in the region.

[d] Average of living mulch and weed cover estimated multiple times during the season.

[e] Oven-dried (two weeks at 75C) dry matter.

Table 3.4. Cover crop and weed parameters in the herbicide-type combinations during 2015.[a, b, c, d]

Herbicide-type combination	**Average CC cover**	**Average weed cover**	**CC cover harv.**	**Weed cover harv.**	**Average CC height**	**CC height harv.**	**CC density**	**Weed density**	**CC biomass**	**Weed biomass**
	(%) [e]				**(cm)** [e]		**(plants m^{-2})**		**(tons ha^{-1})** [f]	
Untreated living mulch check	88 a (7.4)	6 b (2.2)	91 a (10)	4 b (2.2)	104 a (4.8)	95 a (5.2)	87 a (11)	20 a (5)	7 a (0.6)	0.18 b (0.3)
Weedy check	-	47 a (2.2)	-	46 a (2.2)	-	-	-	27 a (5)	-	2.18 a (0.3)
Type 1 + Type 1	72 a (5.3)	8 b (1.6)	93 a (7)	4.8 b (1.6)	84 b (3.7)	87 a (3.8)	93 a (8)	22 a (3.4)	5 ab (0.4)	0.44 b (0.2)
Type 1 + Type 2	70 a (5.4)	4 b (1.6)	54 b (7)	3 b (1.6)	80 b (3.7)	81 a (3.8)	97 a (8)	17 a (3.4)	5 b (0.4)	0.27 b (0.2)
Type 2 + Type 1	78 a (3.4)	4 b (1.2)	85 a (4)	2.8 b (1.2)	81 b (2.8)	82 a (2.7)	99 a (5)	16 a (2.1)	5 b (0.2)	0.14 b (0.1)
Type 2 + Type 2	88 a (7.4)	3 b (2.2)	93 a (10)	2 b (2.2)	86 ab (4.8)	85 a (5.2)	100 a (11)	11 a (5)	5 ab (0.6)	0.06 b (0.3)

[a] Treatments in the herbicide-type combinations: Type 1 + Type 1- s-metolachlor + rimsulfuron and s-metolachlor + fomesafen; Type 1 + Type 2- rimsulfuron + metribuzin and fomesafen + metribuzin; Type 2 + Type 1- metribuzin + rimsulfuron low, metribuzin + fomesafen, metribuzin + rimsulfuron high, imazethapyr + rimsulfuron and imazethapyr + fomesafen; Type 2 + Type 2- metribuzin + halosulfuron.

[b] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test ($\alpha = 0.05$). Standard error is shown in parentheses.

[c] Visual estimations (percentages) were in absolute terms, so living mulch and weed cover may not add to 100%.

[d] Abbreviations: CC, cover crop; harv., during late August, typical vegetable harvest time in the region.

[e] Average of living mulch and weed cover estimated multiple times during the season.

[f] Oven-dried (two weeks at 75C) dry matter.

Table 3.5. Cover crop and weed parameters in the herbicide-type combinations during 2016.[a, b, c]

Herbicide-type combination	Average CC cover	Average weed cover	CC cover harv.	Weed cover harv.	Average CC height	CC height harv.	CC density	Weed density	CC biomass	Weed biomass
	(%) [d]				(cm) [d]		(plants m^{-2})		(tons ha^{-1}) [e]	
Untreated living mulch check	88 a (4.6)	22 bc (5)	95 a (10)	31 bc (10)	64 a (4)	106 a (5)	174 a (20)	103 ab (25)	5.5 a (0.6)	1.1 bc (0.22)
Weedy check	-	57 a (5)	-	98 a (10)	-	-	-	160 a (25)	-	4.2 a (0.22)
Type 1 + Type 1	87 a (3.3)	28 b (4)	93 a (7)	27 bc (7)	65 a (3)	104 a (3)	138 ab (14)	124 ab (19)	3.9 ab (0.4)	1.5 b (0.15)
Type 1 + Type 2	24 b (3.3)	59 a (4)	52 b (7)	55 b (7)	39 b (3)	76 b (3)	103 b (14)	61 b (19)	2.7 b (0.4)	1.3 b (0.15)
Type 2 + Type 1	89 a (2)	13 c (3)	98 a (4)	19 c (4)	60 a (2)	103 a (2)	132 ab (10)	85 b (15)	5.1 a (0.2)	0.6 c (0.09)
Type 2 + Type 2	90 a (4.6)	8 c (5)	97 a (10)	8 c (10)	65 a (4)	114 a (5)	141 ab (20)	81 ab (25)	6.1 a (0.6)	1 bc (0.22)

[a] Treatments in the herbicide-type combinations: Type 1 + Type 1- s-metolachlor + rimsulfuron and s-metolachlor + fomesafen; Type 1 + Type 2- rimsulfuron + metribuzin and fomesafen + metribuzin; Type 2 + Type 1- metribuzin + rimsulfuron low, metribuzin + fomesafen, metribuzin + rimsulfuron high, imazethapyr + rimsulfuron and imazethapyr + fomesafen; Type 2 + Type 2- metribuzin + halosulfuron.

[b] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test ($\alpha = 0.05$). Standard error is shown in parentheses.

[c] Visual estimations (percentages) were in absolute terms, so living mulch and weed cover may not add to 100%.

[d] Abbreviations: CC, cover crop; harv., during late August, typical vegetable harvest time in the region.

[e] Average of living mulch and weed cover estimated multiple times during the season.

[f] Oven-dried (two weeks at 75C) dry matter.

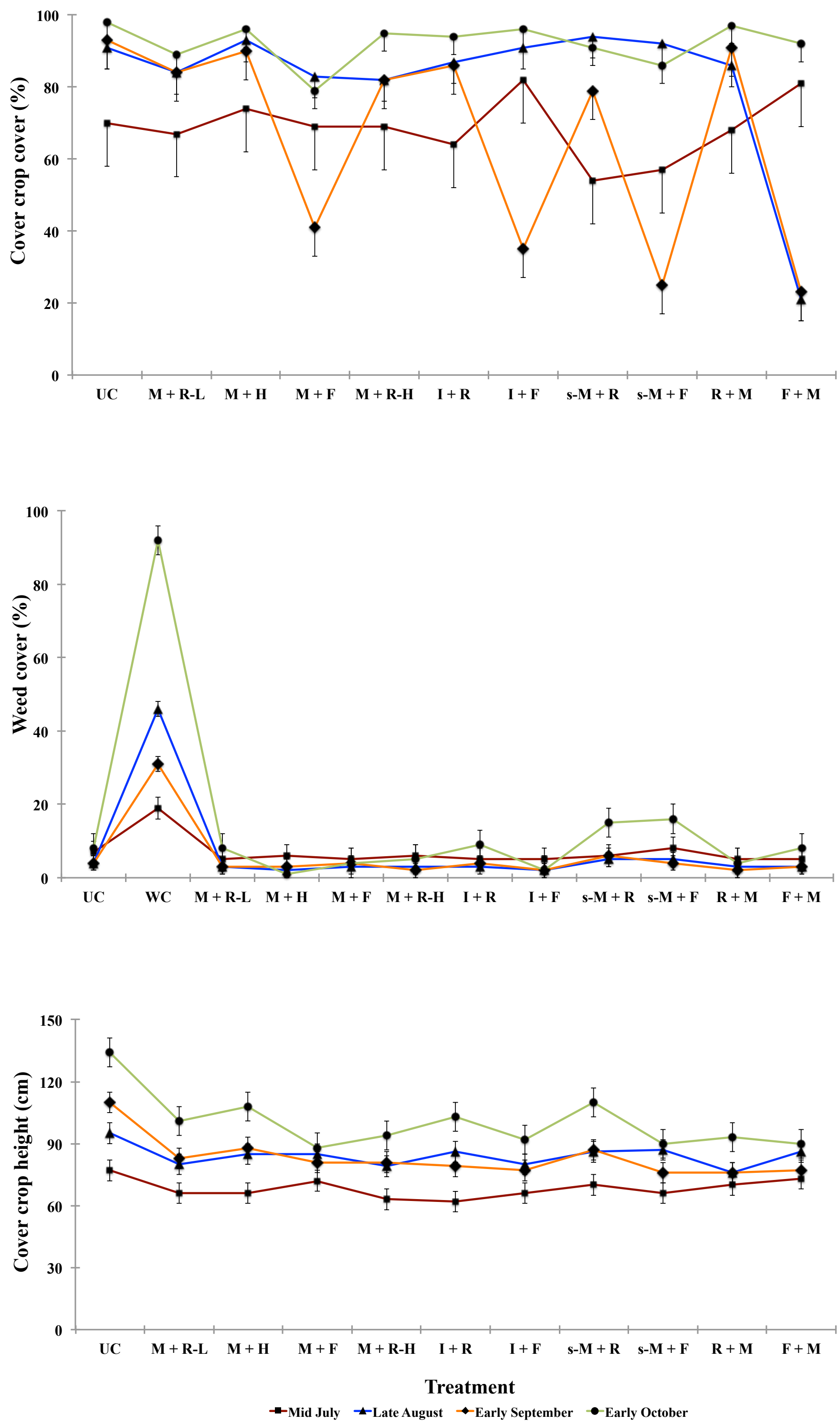

Figure 3.1. Cover crop cover (top), weed cover (center) and cover crop height (bottom) (± SE) at different times during 2015. Abbreviations for treatments: UC, untreated living

mulch check; WC, weedy check; F, fomesafen; H, halosulfuron; I, imazethapyr; M, metribuzin; R, rimsulfuron; s-M, s-metolachlor; M + R-L, metribuzin 0.05 + rimsulfuron 0.005; M + R-H, metribuzin 0.1 + rimsulfuron 0.007.

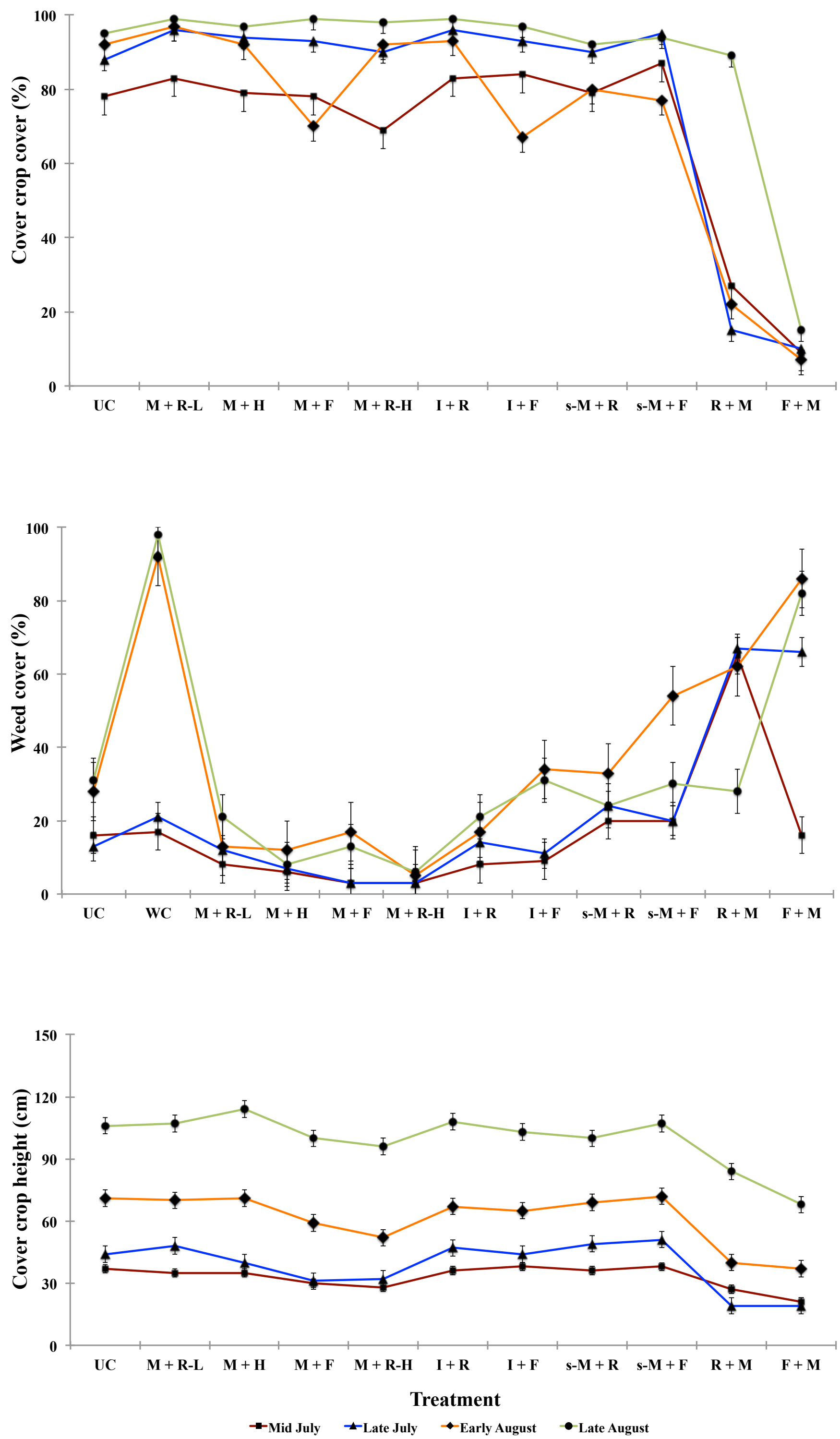

Figure 3.2. Cover crop cover (top), weed cover (center) and cover crop height (bottom) (± SE) at different times during 2016. Abbreviations for treatments: UC, untreated living

mulch check; WC, weedy check; F, fomesafen; H, halosulfuron; I, imazethapyr; M, metribuzin; R, rimsulfuron; s-M, s-metolachlor; M + R-L, metribuzin 0.05 + rimsulfuron 0.005; M + R-H, metribuzin 0.1 + rimsulfuron 0.007.

APPENDIX

Table 1. Tomato yield, and living mulch and weed parameters in the inoculated living mulch test during 2016.[a, b, c, d]

Treatment	Tomato yield	Average LM cover	Average weed cover	LM cover harv.	Weed cover harv.	Average LM height	LM height harv.	LM density	Weed density	LM biomass	Weed biomass
	(tons ha^{-1})	(%) [e]				(cm) [e]		(plants m^{-2})		(tons ha^{-1}) [f]	
Control	101 a	-	-	-	-	-	-	-	-	-	-
Untreated living mulch	29 cd	82 a	25 c	87 ab	19 b	77 a	116 b	132 a	84 ab	2.8 b	2.1 b
Weedy check	37 cd	-	98 a	-	98 a	-	-	-	141 a	-	9 a
Rimsulfuron + Metribuzin	60 b	42 b	49 b	78 b	29 b	40 b	75 c	133 a	55 b	1.3 c	1.4 b
I- Untreated living mulch	20 d	87 a	34 bc	99 a	34 b	85 a	141 a	93 ab	99 ab	4.7 a	1.5 b
I- Rimsulfuron + metribuzin	44 bc	35 b	41 bc	79 b	33 b	41 b	86 c	79 b	61 b	2.3 bc	1.1 b

Standard error	5	4	5	6	8	3	4	11	13	0.3	0.8

[a] Data from the following treatments have been adopted from the main tomato trial (in 2016) in order for comparison with the inoculated treatments: Control, untreated living mulch check, weedy check and rimsulfuron + metribuzin.

[b] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test ($\alpha = 0.05$).

[c] Visual estimations (percentages) were in absolute terms, so living mulch and weed cover may not add to 100%.

[d] Abbreviations: LM, living mulch; harv., at beginning of tomato harvest; I, Inoculated.

[e] Average of living mulch and weed cover estimated multiple times during the season.

[f] Oven-dried (two weeks at 75C) dry matter.

Table 2. Nutrient concentrations in tomato leaf tissue at different times in the treatments from the inoculated living mulch test, and its non-inoculated counterparts in the main tomato trial, during 2016.[a, b, c]

Treatment	N	P	K	Ca	Mg	S	Mn	Fe	Cu	B	Zn
	(%)						(ppm)				
First sampling (at peak tomato flowering)											
Control	3.5 a	0.29 a	3.1 bc	1.9 a	0.34 b	0.67 b	42 c	114 ab	8.7 a	16 a	26 a
Untreated living mulch check	3.4 a	0.32 a	3.8 ab	1.8 a	0.4 ab	0.83 a	58 abc	110 ab	9 a	17 a	25 a
Weedy check	2.7 b	0.28 a	3.1 c	1.9 a	0.34 b	0.72 ab	43 c	104 b	7.3 a	17 a	17 a
Rimsulfuron + metribuzin	3.4 a	0.28 a	3.2 bc	2 a	0.38 ab	0.73 ab	55 bc	115 ab	7.5 a	16 a	18 a
I- Untreated living mulch check	3.4 ab	0.3	4.1 a	2 a	0.44 a	0.84 a	76 a	130 ab	9.4 a	15 a	17 a
I- Rimsulfuron + metribuzin	3.3 ab	0.3	3.5 abc	2 a	0.4 a	0.77 ab	70 ab	137 a	8.7 a	14 a	16 a
Standard error	0.2	0.01	0.14	0.08	0.02	0.03	5	7	0.6	1	5
Second sampling (at harvest time)											
Untreated living mulch check	2.7 b	0.26 bc	2.9 b	3 a	0.36 c	0.93 a	67 b	117 bc	6.8 bc	25 ab	12 a

Rimsulfuron + metribuzin	2.7 b	0.22 c	2.5 b	2.8 a	0.37 bc	0.75 a	66 b	88 c	5.3 c	24 b	11 a
I- Untreated living mulch check	3.8 a	0.42 a	3.9 a	3.6 a	0.53 a	1.17 a	113 a	211 a	11 a	35 a	15 a
I- Rimsulfuron + metribuzin	3.2 ab	0.31 b	2.8 b	3.7 a	0.45 ab	1.16 a	87 ab	145 b	7.9 b	27 ab	12 a
Standard error	0.2	0.02	0.14	0.3	0.02	0.17	8	10	0.6	2	1.3

[a] Data from the following treatments have been adopted from the main tomato trial (in 2016) in order for comparison with the inoculated treatments: Control, untreated living mulch check, weedy check and rimsulfuron + metribuzin.

[b] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test ($\alpha = 0.05$).

[c] Abbreviations: N, nitrogen; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; S, sulfur; Mn, Manganese; Fe, iron; Cu, copper; B, boron; Zn, zinc; I, inoculated.

Table 3. Nutrient concentrations in sunnhemp tissue at different times in the treatments from the inoculated living mulch test, and the non-inoculated treatments in the main tomato trial, during 2016.[a, b, c]

Treatment	N	P	K	Ca	Mg	S	Mn	Fe	Cu	B	Zn
				(%)					(ppm)		
First sampling (at peak tomato flowering)											
Untreated living mulch check	2.5 b	0.31 ab	2 a	1.7 ab	0.32 a	0.37 ab	57 a	134 a	6.6 ab	16 a	37 a
Metribuzin + halosulfuron	2.7 b	0.31 ab	2 a	1.6 b	0.32 a	0.35 b	34 a	99 a	5.9 b	15 a	30 a
Metribuzin + rimsulfuron	2.8 b	0.35 a	1.8 a	2 a	0.38 a	0.47 a	38 a	120 a	6.6 ab	17 a	29 a
Fomesafen + metribuzin	2.7 b	0.3 b	1.8 a	1.6 ab	0.36 a	0.36 ab	37 a	123 a	6.1 b	15 a	33 a
Rimsulfuron + metribuzin	2.9 b	0.32 ab	2.1 a	1.4 b	0.35 a	0.36 ab	29 a	95 a	6.7 ab	13 a	29 a
I- Untreated living mulch check	3.6 a	0.3 ab	2.1 a	1.4 b	0.34 a	0.29 b	75 a	150 a	6.5 ab	13 a	24 a
I- Rimsulfuron + metribuzin	3.6 a	0.35 ab	2.2 a	1.4 b	0.35 a	0.35 b	49 a	144 a	7.8 a	13 a	26 a
Standard error	0.2	0.01	0.1	0.1	0.02	0.02	11	20	0.3	1	4

Second sampling (at harvest time)											
Untreated living mulch check	1.9 b	0.4 a	1.4 a	2 a	1.28 a	0.54 a	54 a	130 a	5.8 a	19 a	29 a
Rimsulfuron + metribuzin	2 b	0.35 a	1.4 a	1.9 a	0.28 a	0.45 a	33 a	94 a	4.1 b	17 ab	24 ab
I- Untreated living mulch check	3.8 a	0.33 a	1.6 a	1.7 a	0.28 a	0.32 b	75 a	172 a	5 ab	14 bc	22 ab
I- Rimsulfuron + metribuzin	3.7 a	0.33 a	1.6 a	1.7 a	0.27 a	0.32 b	42 a	118 a	4.4 b	12 c	20 b
Standard error	0.2	0.03	0.08	0.1	0.01	0.03	11	20	0.4	0.8	2

[a] Data from the following treatments have been adopted from the main tomato trial (in 2016) in order for comparison with the inoculated treatments: Untreated living mulch check, metribuzin + halosulfuron, metribuzin + rimsulfuron, fomesafen + metribuzin and rimsulfuron + metribuzin.

[b] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test (α = 0.05).

[c] Abbreviations: N, nitrogen; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; S, sulfur; Mn, Manganese; Fe, iron; Cu, copper; B, boron; Zn, zinc; I, inoculated.

Table 4. Tomato canopy width in the non-inoculated treatments of the main tomato trial, and in the inoculated living mulch test during 2016.[a, b, c, d]

Treatment	Tomato canopy width (cm)
Control	101 a
Untreated living mulch	60 bc
Weedy check	31 d
Metribuzin + halosulfuron	80 ab
Metribuzin + rimsulfuron	81 ab
Fomesafen + metribuzin	74 b
Rimsulfuron + metribuzin	77 ab
I- Untreated living mulch check	39 cd
I- Rimsulfuron + metribuzin	67 b
Standard error	5

[a] Values within each column not followed by a same letter(s) are significantly different according to Tukey's test ($\alpha = 0.05$).

[b] Abbreviations: I, inoculated.

[c] Measurements were made during harvest time.

[d] Tomato row spacing was 122 cm.